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in
Experimental Physics

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Preface

IT is the purpose of this book to describe important procedures in experimental physics. Subjects of special interest and value to the authors in their own investigations have been selected for treatment. Many of the procedures and results of research appear here in print for the first time.

The ideal way to learn the procedures of experimental physics is by direct contact with them in the laboratory. Realizing this, we have endeavored to bridge the gap between laboratory demonstrations and experience on the one hand, and exposition on the other, by the liberal use of figures.

I am indebted to Mr. D. O. Hendrix for most of the procedures presented in Chapter II, and to Dr. R. M. Langer for the treatment of the unsteady flow of heat presented in Chapter XII.

I have drawn freely from many books and scientific periodicals. It is hoped that there are no lapses in my effort to acknowledge adequately the source of this material.

The assistance of my wife, of Mrs. Elizabeth H. Hayward, and of Mr. James T. Barkelew in the preparation of the manuscript is gratefully acknowledged, as is also the helpfulness and courtesy of the Prentice-Hall editors.

J. S.

Contents

CHAPTER I

Fundamental Operations in Laboratory Glass Blowing

THE fundamental operations in glass blowing for laboratory use are cutting, rotating, bending, blowing, and welding. By various combinations of these operations, apparatus is constructed from glass tubing and glass cane. It is the purpose of this chapter to describe how these operations are executed. Hard glass, such as Pyrex, is now used extensively for making laboratory apparatus. It is more difficult to manipulate than soft glass because it has a higher working temperature and thus congeals quickly when it is removed from the flame. However, less difficulty is experienced in annealing hard glass because of its low thermal expansion and high strength. Since this more than outweighs the greater skill required for manipulation, we will be concerned chiefly with hard glass in this chapter.[1]

An arrangement of a glass-blowing workbench is shown in Fig. 1. Cross-fires are shown for heating the glass to softness, a method that may be termed American, since German glass blowers ordinarily use a single-blast burner. Compared with the blast burner, cross-fires heat the glass more rapidly and uniformly. Either method may be used for most of the operations. However, some of them require a pointed flame, which is more easily obtained with a blast burner.

Here, where we treat of the American method, the hand torch, mounted as shown by the dotted lines in Fig. 1, is used to obtain the pointed flame. Natural or artificial gas

[1] Glass may be obtained from the Corning Glass Company, Corning, New York.

is used for fuel in the burners. Compressed air is used for working soft glass; but in order to obtain the higher temperature required to work hard glass, oxygen or a mixture of oxygen and air must be used. In an ordinary blast burner, however, acetylene can be used as fuel with compressed air.

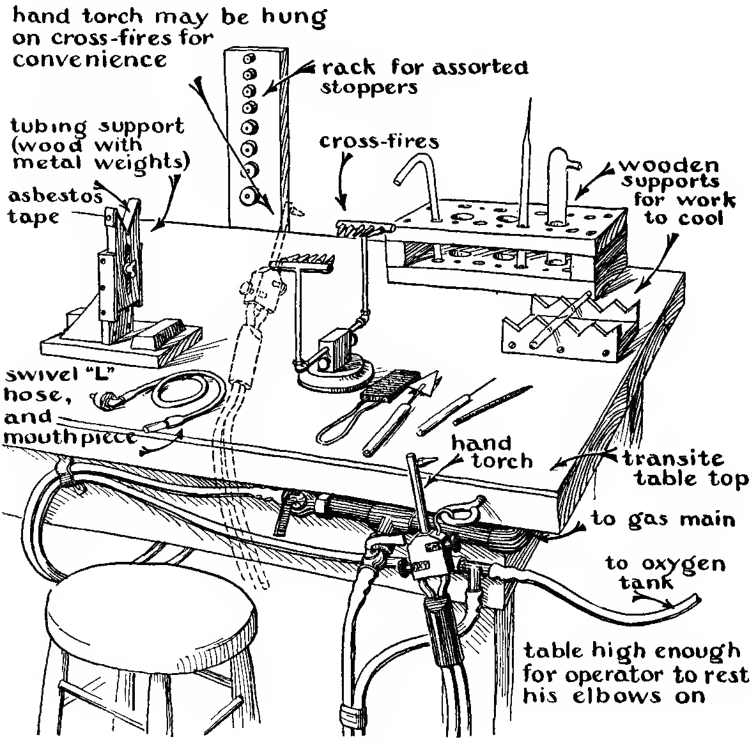

Fig. 1.

Accessory equipment includes a collection of corks of various sizes, some fitted with closed glass tubes to serve as handles for rotating the work, and others with open tubes for blowing. Pieces of rubber hose of various sizes fitted with closed glass tubes, to close up the ends of small tubes, are also included. A swivel L and mouthpiece device with a connecting rubber hose, shown in Fig. 1, is convenient for blowing rotated work that is large or otherwise awkward to

bring to the mouth. Forceps and molding tools used for spinning glass are shown in Fig. 2. A file for cutting small tubes and a hot-wire device for cutting larger tubes are shown in Fig. 3. To sharpen the corners of the file, the narrow sides are ground on an emery wheel. When the file

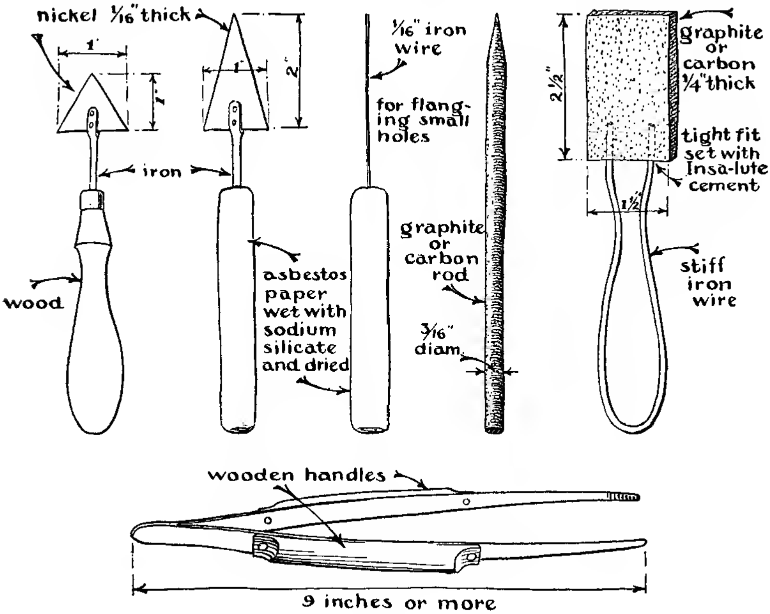

Fig. 2.

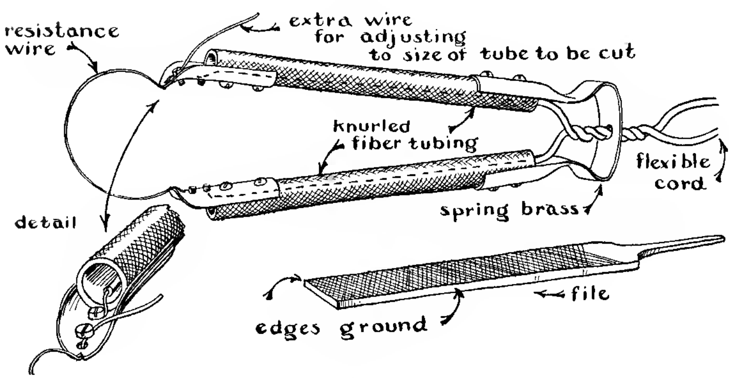

Fig. 3.

requires tempering, it is heated until it becomes a dull red and plunged into cold mercury.

Pyrex tubes of various sizes, capillaries, and cane are kept in stock for constructing apparatus. There should also be a supply of other glasses, such as soda glass, lead glass, and

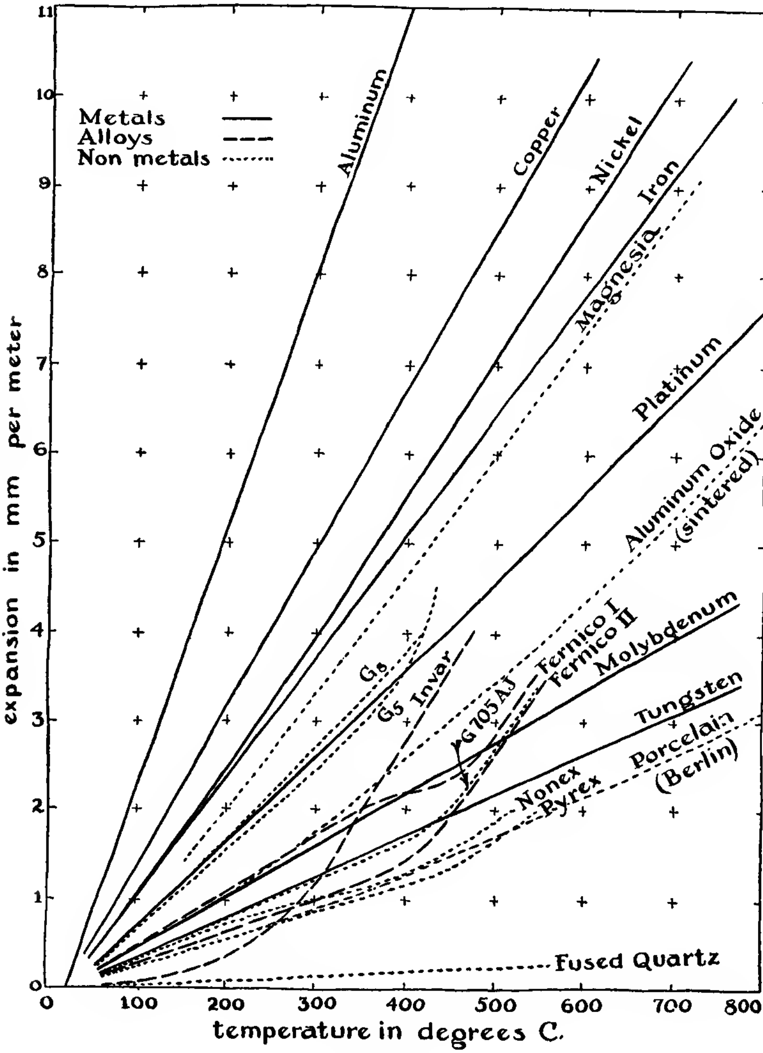

Fig. 4.

Nonex. These should be well labeled and kept apart from the main stock.

Some physical properties of glass. The thermal expansion of various glasses and metals is shown in Fig. 4 and Table I. Other characteristic temperatures of glass and quartz are given in Table II. The variation of viscosity

TABLE I

THERMAL EXPANSION COEFFICIENTS

Material	Expansion Coefficient ($\times 10^7$)
Lime glass (G8)	92
Lead glass (G5)	90
Nonex (G702P)	36
Porcelain (20° to 290° C.)	41
Pyrcx	32
Quartz glass (16° to 1000° C.)	5.8
Copper	162
Platinum	91
Dumet:	
radial	80 to 100
axial	61 to 65
Fernico and Kovar:	
25° to 450° C.	47
25° to 500° C.	56
Molybdenum	56
Tungsten	47

TABLE II

CHARACTERISTIC TEMPERATURES FOR GLASS AND QUARTZ

Material	Strain Point	Annealing Temperature	Working Temperature
Soft glass	389° C.	425° C.	....
Nonex	486°	521°	....
Pyrex	503°	550°	750° to 1100° C.
Quartz	1020°	1120°	1756° to 1800°

with temperature for a typical glass is shown in Fig. 5. The viscosities corresponding to important characteristic temperatures—annealing temperature, working temperature, and melting temperature—are indicated on the curve in Fig. 5. The significance of the first two temperatures is

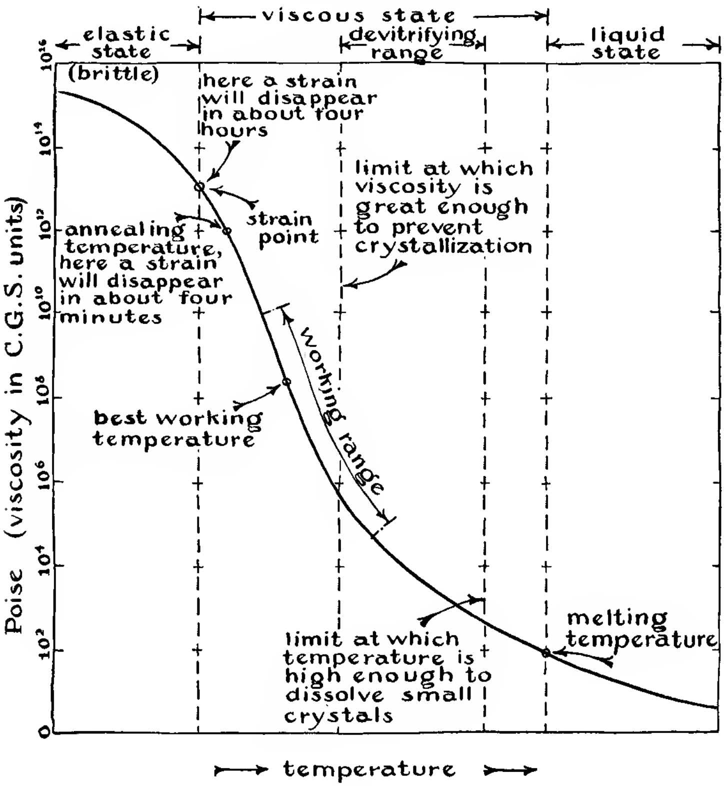

Fig. 5.

that internal strain is relieved in about 4 hours when glass is heated to the yield point, while only about 4 minutes are required at the annealing temperature. At the yield point the viscosity is about 10^{13} poise. At the annealing temperature it is about 10^{12} poise. In the working range of temperature the viscosity varies between the limits 10^5 and 10^{10} poise, with the optimum working viscosity about $10^{8.6}$ poise.

Glass is considered molten when the viscosity is less than 10^2 poise.

Cutting tubes and bottles. To cut small glass tubes (to $\frac{1}{2}$ inch in diameter) for the operations of glass blowing,

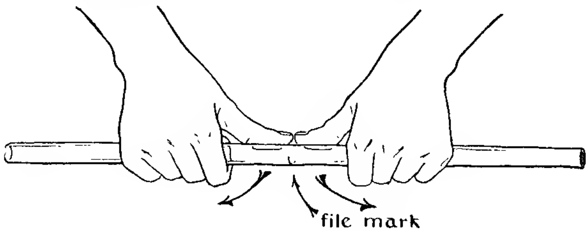

Fig. 6.

they are first scratch-marked with the sharp edge of a file, care being taken that the scratch, a few millimeters long, is accurately perpendicular to the tube. A break is then made by a combined bending and pulling force as illustrated in Fig. 6. Tubes can be broken at the scratch-mark by means of a stroke with the file as shown in Fig. 7. This technique is suitable when the tube is hot or when it is to be cut near the end.

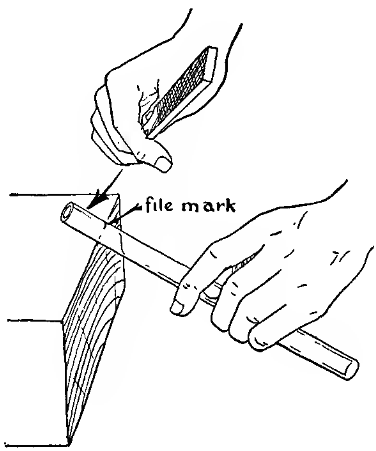

Fig. 7.

Tubes larger than $\frac{1}{2}$ inch in diameter require a different technique. After being scratch-marked with the file, they may be cracked by applying the tip of a small piece of glass cane, made incandescent in the flame, to one end of the file mark. The crack thus produced may or may not completely encircle the glass. If not, it can be made to do so by leading it with repeated applications of the glowing cane tip, each application being just ahead of the end of the crack.

A tube or bottle of several inches in diameter is cut by first filing a narrow scratch-mark around its circumference. A piece of stiff paper or cardboard may be used to guide the file in making this mark. The wire of the device shown in Fig. 3 is adjusted to fit in the mark. The ends of the wire must not touch. An electric current is passed through the wire, heating it to a red heat for a few seconds, and water is applied to the scratch-mark and wire with a pad of wet cotton. This procedure will produce a clean crack around the circumference. Small irregularities in the crack may be removed by grinding on a brass plate with Carborundum grits, or after the glass has been softened in the flame they may be pulled off with forceps or cut off with shears.

Cleaning. Good welds cannot be made with contaminated glass. Therefore, the first operation after cutting should be cleaning. Sometimes washing with water is sufficient, but nitric acid may be substituted if necessary. In extreme cases, hot chromic acid "cleaning solution" may be required. Water used to rinse glass tubing is removed from the outside with a clean cloth and from the inside with a wad of cotton pulled through with a string or blown through with air. Or, if distilled water is used, the tube may be dried by drawing air through it with a water aspirator and by warming it gently at the same time.

Preheating. Glass tubing and especially large glass apparatus must be preheated carefully before they can be safely exposed to the local intense heat of the cross-fires or hand torch. By one procedure for preheating, the work is first exposed to the relatively cool flame of a Meker burner with the air shut off. As the glass temperature rises, more and more air is admitted to the Meker burner, giving a hotter and hotter flame, until finally, when the work is thoroughly heated, it is safe to expose it to the intense heat of the cross-fires or blast burner. By an alternative procedure the work is exposed to the heat of the cross-fires for a fraction of a second, after which it is quickly withdrawn to allow temperatures to equalize, and then after a few seconds another

section of the work is exposed. This operation is repeated in such a way that the temperature of the work as a whole is uniformly elevated. The exposure to the flame is increased and the interval outside the flame decreased as the heating progresses, until the work is brought to a temperature at which it distills enough sodium vapor to make the flame yellow. This sodium test usually indicates a temperature at which it is safe to begin the operations of shrinking, blowing, molding, and so forth. Some things, such as tubes, require preheating only in the zone around the region to be worked.

The rotation of the work. Rotation of work is a fundamental operation. It should be executed uniformly and with good coördination of the two hands. Glass properly rotated in the flame becomes uniformly soft, and the effect of gravity on it is symmetrical.

The lower surfaces of hot glass cool more rapidly than the upper surfaces. For this reason it is also important to continue uniform rotation even after the work is removed from the flame.

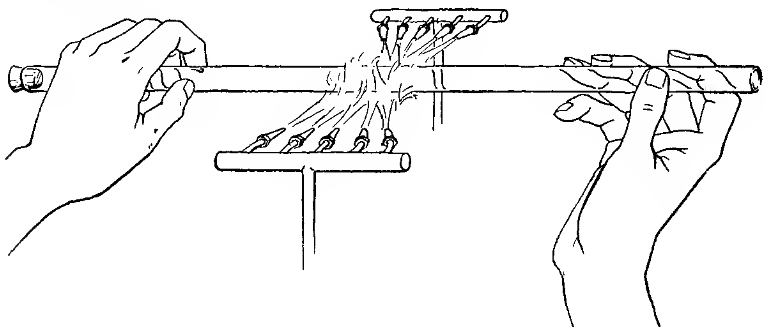

Fig. 8.

The beginner will have difficulty manipulating the work in the flame, particularly after the glass connecting the two parts on either side of the flame becomes soft, when he may "tie up" the work. To avoid this, he is advised to practice rotation with a model consisting of two glass tubes connected with fairly heavy cloth. He should be able to rotate these in the manner shown in Fig. 8, so that the cloth does not

wrinkle or twist and is under neither compression nor tension. He is then ready to begin operations with the flame.

The work is manipulated by the thumbs and forefingers so that, despite differences in diameter, the sections of the work on either side of the soft zone in the flame are rotated in synchronism, the motion consisting of a series of angular displacements of about 45°. The left hand always handles the heavier section of the glass, while the right manipulates the section beyond the soft zone. The right hand has the more delicate though lighter task, since it must rotate its section in phase and without undesired stretching or compression relative to the main section of the work. The hands are held as shown in Fig. 8 to facilitate the application of the right end of the work to the lips for blowing.

Bending tubes. A tube to be bent is heated in the crossfires with continued rotation until it is quite soft along a length equal to several diameters. It is then removed from the flame and bent to the desired angle with the apex down as shown in Fig. 9. As large tubes are difficult to heat uniformly, imperfections often occur. They are also present in small tubes, particularly in small, thin-walled tubes, that have been bent to a sharp angle. Imperfections are worked out in every case by local heating with a pointed flame. When one portion of the tubing wall is heated until it is soft, the general form of the bend is maintained by the portion on the opposite side of the axis of the tube. If the outside tends to flatten as shown in Fig. 9(b), it is corrected by blowing while the glass is soft. If the inside surface folds

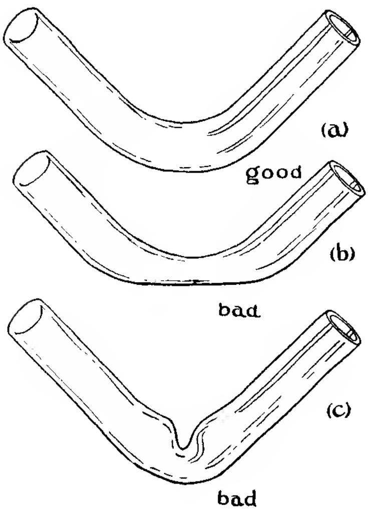

Fig. 9.

as shown at (c), it is locally heated with a sharp pointed flame and worked by alternating shrinking with blowing until it is uniform. These corrections are followed by a general heating to anneal the whole bend.

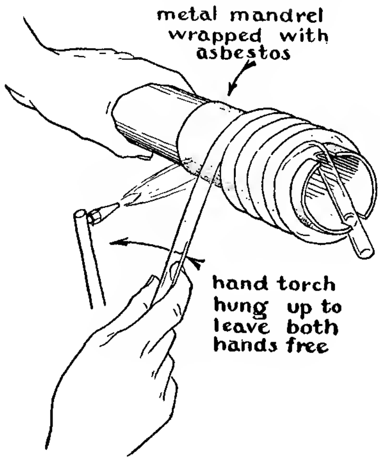

Fig. 10.

A glass coil is made on a mandrel. The mandrel is usually either a steel or brass tube covered with asbestos paper. The paper is applied wet, the ends being lapped and cemented with sodium silicate. After the paper is dry, this lap joint is sandpapered. One or more coats of stove polish or some other form of carbon will prevent the glass from adhering to the asbestos. Notches in the end of the tube secure the coil to the mandrel. The procedure is illustrated by Fig. 10.

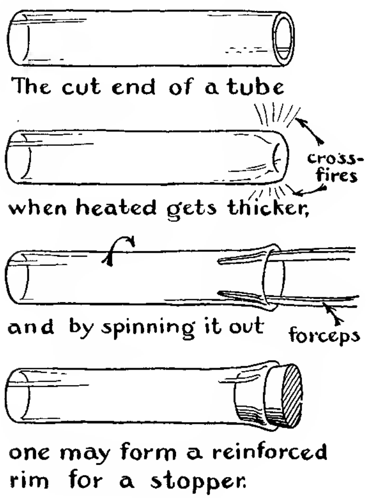

Fig. 11.

Shrinking. Since softened glass is a liquid, its surface tension tends to deform it in such a way that the total surface is decreased. Shrinking at elevated temperatures is restrained by the viscosity of the glass, and this restraint is greater at the lower limit of the working range. Shrinking may yield both desirable and undesirable changes in the work and it is controlled by the use of spinning tools and by blowing into the work. Fig. 11 shows the use of forceps to counteract the undesirable

tendency of the end of a tube to decrease its diameter by shrinking, while the desirable effect of increased wall thickness is achieved.

Annealing. The annealing of complicated and elaborate work is one of the most difficult operations in glass blowing. It is also an important one, since, if the work is not properly annealed, it may break in cooling or, what is worse, fail after it is put into operation. The purpose of annealing is to bring the glass from the working temperature to room temperature with the introduction of a minimum amount of strain. Annealing is properly executed when all parts of the work are maintained at a uniform temperature while the glass is gradually cooled. Large, complicated work should be annealed in a suitably regulated oven. Small work in which the wall thicknesses are uniform can be successfully annealed either with a Meker burner or in the cross-fires.

When the manipulations have been completed, the work is heated until it is above the annealing temperature. The temperature is then gradually lowered by applying the procedures of preheating in reverse order. It is important that the temperatures be kept uniform during the cooling by special extra applications of heat on those parts which tend to cool more rapidly, either because they are thinner or because they are subject to greater heat losses by radiation and convection. When the temperature is judged to be well below the strain point, the work may be set aside for final cooling in a place free from drafts.

Pulling a point. "Pulling a point" is a technical term used by glass blowers indicating that a tube is heated in the flame and drawn out as illustrated in Fig. 12 to give a "point," which is usually some 6 inches in length. The point may have several functions. It may serve as a handle for rotation or, with the tip removed, as a mouthpiece through which to blow; or it may afford a means of closing the work. Also, pulling a point is a preliminary to several other operations.

We will assume, for the purpose of our discussion here, that a section of tubing is required with points on both ends as an

element of some apparatus under construction, and furthermore that this is to be obtained from a longer stock tube. First, a point is pulled on the end of the stock tube. If it is long, the stock tube may be supported on the left by a

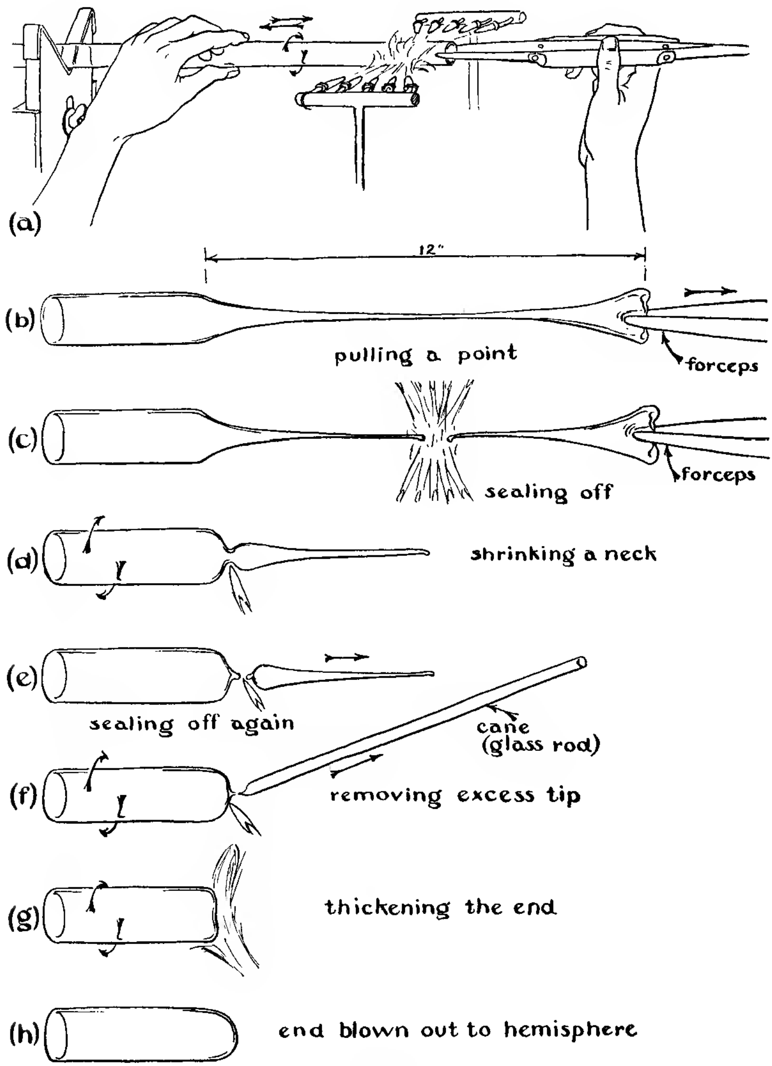

Fig. 12.

V-block as shown at (a) in Fig. 12. After preheating the tube by the second procedure outlined above, it is softened a few diameters back from the end. Then the glass is gathered together at the tip with forceps; the work is removed from the flame, and with continued rotation the soft glass is drawn out as shown at (b). The capillary section is fused in the middle as shown at (c), or, if the point is to serve as a mouthpiece, it may be cut and fire-glazed by momentary exposure to a flame.

The tubing is then heated until it is soft at a suitable distance back of the first point, and the desired section is drawn off, forming at the same time the second point.

It is important to have the walls of the point symmetrical about the axis of the tube. Errors may be corrected by heating the shoulder of the point until it is soft and manipulating the glass from the end of the capillary. It is advisable to work the glass at a low temperature when making corrections.

Closing a tube. Pulling a point is the first operation in closing a tube as shown in Fig. 12(d) to (h). The point is removed with a sharp flame as shown at (d) and (e). Excess glass at the tip is removed with forceps or with a piece of cane (f), and the end is then heated to shrink it (g); then it is blown to the final hemispherical shape (h). The hand torch is usually used for this operation.

"Cutting" a tube in the fire. The first step in "cutting" a tube in the fire is to pull a point. Again the point is removed as described above, Fig. 12(d) and (e), and excess glass removed, Fig. 13(a). The end is then heated (b) and blown with a strong puff to yield a thin kidney-shaped bulb (c), which is broken off with the file or forceps as shown at (d). The edges are now heated to shrink them and thicken them to the size of the tubing elsewhere (e). The diameter is increased by a spinning process and the use of forceps as in (f) or flanging tool as in (g). If forceps are used, they are introduced and allowed to expand slowly as the glass is rotated in the fire. The end of the tube is then

squared with the carbon plate (h). If a flange is required, the end is spun out with the arrowhead spinning tool and squared with the carbon plate as shown at (h) and (i). Metal spinning tools are wet with beeswax to prevent sticking to soft glass.

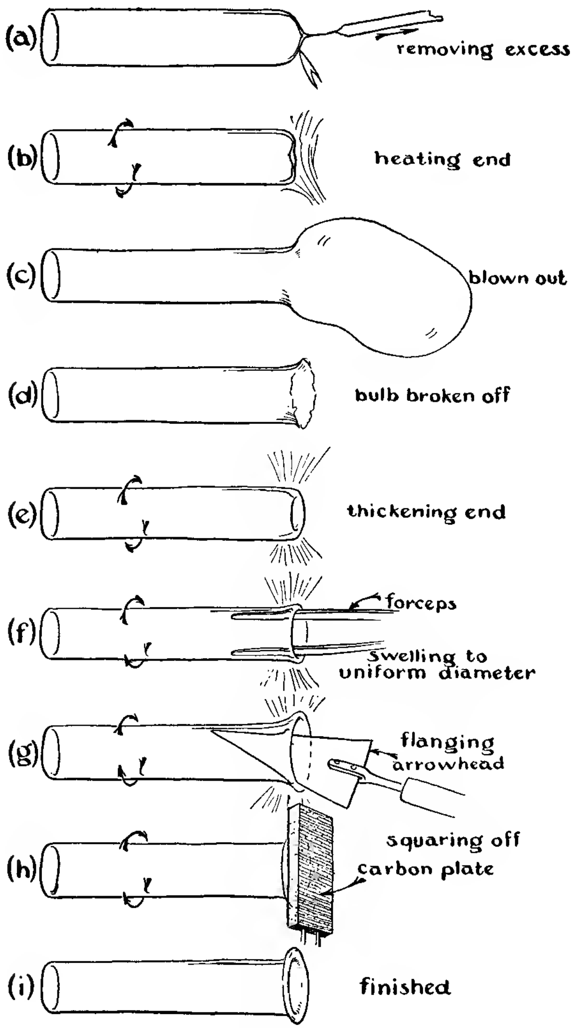

Fig. 13.

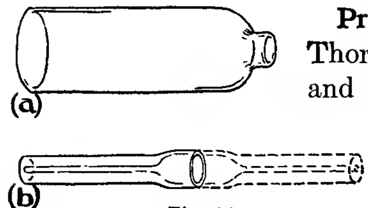

Fig. 14.

Preparations for making joints. Thorough cleaning of the glass tube and careful attention to the preliminaries of cutting, flanging, or drawing and expanding it facilitate the manipulations in the flame. A common fault in the beginner is that he thinks he can easily correct deficiencies in these operations after the work is in the flame. It is significant that good glass blowers do not handicap themselves by carelessness with these preliminaries.

The elements that are to be welded to form a joint must have approximately the same diameter and wall thickness. If a large tube is to be joined to a smaller one, the large tube is first prepared as shown in Fig. 14(a) by pulling a point on it and then cutting off the point in the flame where the shoulder has the same diameter as the small tube.

A capillary or thick-walled tube is prepared as shown at (b). It is heated to softness and blown until it has the proper wall thickness and then pulled until it has the same diameter as the tube to which it is to be sealed.

A bulb or cylinder to which a small tube is to be joined is

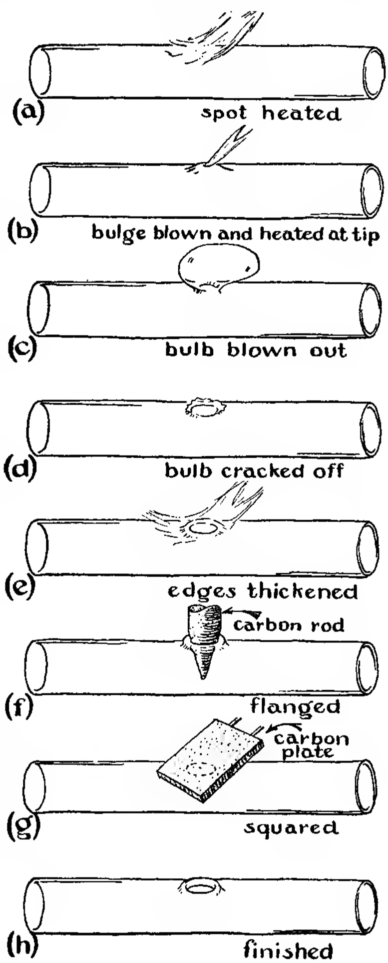

Fig. 15.

first preheated. A soft flame is then directed on the place selected for the joint until it is soft, and a slight bulge is blown as shown in Fig. 15(a). This bulge is strongly heated at its apex with the tip of a sharp flame as at (b). Then, after removing it from the flame, a small thin-walled bulb is blown as at (c). This is then broken off with the forceps or file. The edges of the hole thus made are softened with the flame, flanged with the carbon taper, and squared with the carbon plate as shown in Fig. 15(d) to (h).

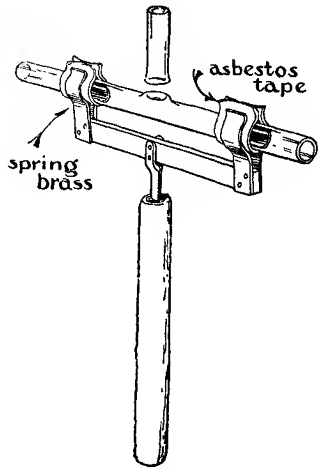

Fig. 16.

A straight tube is prepared for making **T**'s by opening the side as described above. When several **T**'s are to be made, a holder for the straight-through tube as shown in Fig. 16 is convenient. **Y**'s are made by first bending a tube to an acute angle. This is then opened at the apex as shown in Fig. 17.

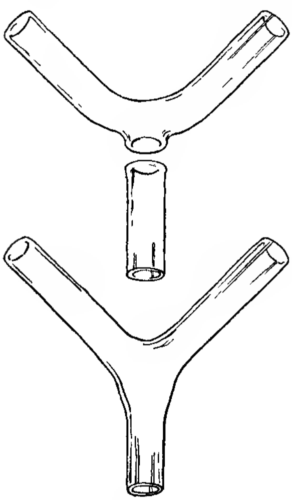
Fig. 17.

Making a joint. The elements are heated with rotation in a flame whose diameter is approximately the same as the diameter of the tubes. They are arranged facing each other, as shown in Fig. 18, with the axis of the joint perpendicular to that of the flame. When the tubes are thoroughly soft at their ends, they are removed from the flame and touched together at right angles as shown at (b). This contact is used as a hinge to steady the hands while the tubes are brought

into exact register and pushed together (c). With continuous rotation, the joint is held in the flame until it shrinks to a uniform outside diameter (d). It is then withdrawn from the flame and blown out until it has a uniform

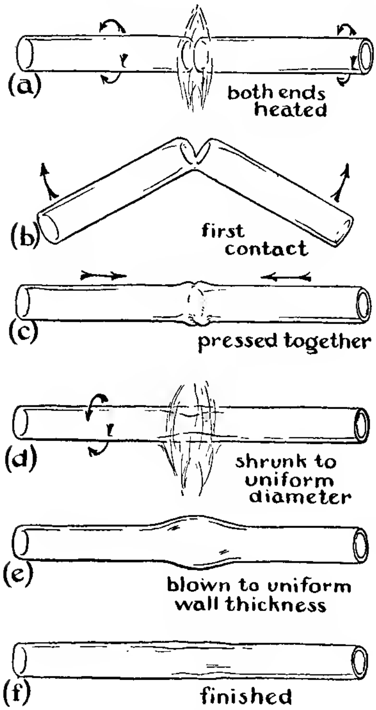

Fig. 18.

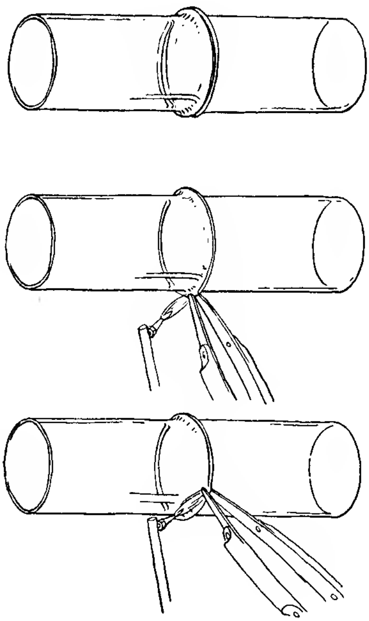

Fig. 19.

wall thickness (e), and stretched at once to a uniform outside diameter (f). Since it is necessary to blow a joint, obviously all openings except the one applied to the lips must be temporarily closed.

Large tubes that are to be joined must have flanges. When it is necessary to make a joint on apparatus which cannot be rotated, the squared ends of the elements of the joint are accurately fitted together and heated, a section of the circumference at a time. The welding of the flanges is effected with the heat of the hand torch and pressure applied

with the forceps working around the circumference as shown in Fig. 19. After this the joint is locally heated, a small section of the circumference at a time, until it is soft, and the softened area is worked by alternate shrinking and blowing until the wall is smooth. Then the whole circumference is uniformly heated for final blowing, alignment, and annealing.

Ring seals. When a tube is inserted in a bulb or a larger tube, a ring seal joins the tubing wall to the edge of the aperture in the bulb or large tube. First, the glass around the

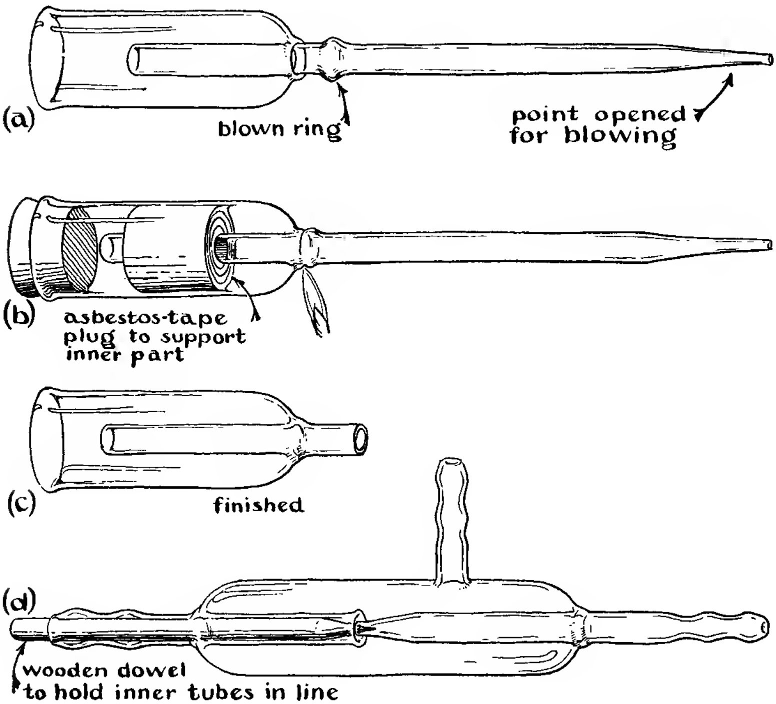

Fig. 20.

aperture is accurately molded with the carbon taper until it is slightly larger than the outside diameter of the small tube to be inserted. The small tube is prepared for the seal by heating a narrow zone around its circumference with a pointed flame and swelling it as shown in Fig. 20(a). This

is accomplished by blowing and simultaneously applying a longitudinal compression. The small tube is then inserted and held exactly concentric with the larger tube by an improvised support, such as a roll of asbestos paper, as illustrated in Fig. 20(b). The place to be sealed is exposed to a pointed flame with continued rotation until the glass at the ring is soft. Then the weld is made by pushing the swelling of the smaller tube against the constricted opening of the larger tube. The work is removed from the flame, blown, and aligned, while at the same time the small tube is given a slight pull. Fig. 20 shows the construction of a water aspirator which requires two ring seals. A tapered wooden dowel which just slips into the first tube centers the second while it is being sealed. Ring seals require careful annealing.

Another procedure for ring seals, particularly suited for inserting a small tube through the side of a larger tube, is

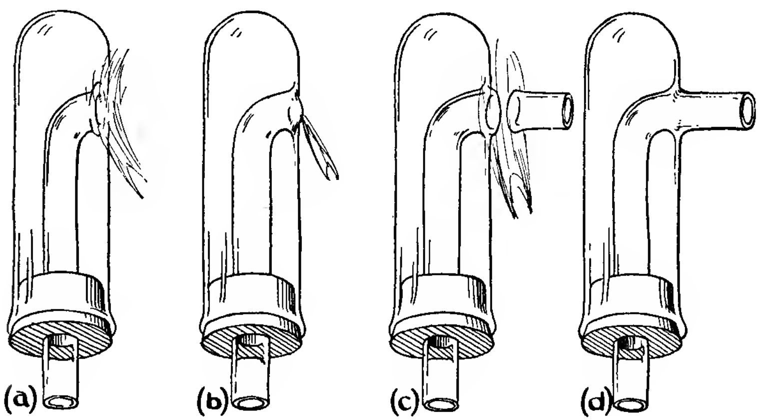

Fig. 21.

illustrated by Fig. 21. The inner section of the insert is flanged and molded to conform to the inside wall of the large tube and is supported in contact with it as shown at (a). The area of the outside wall of the large tube opposite the place where the section makes contact on the inside is then heated until the two tubes are sealed together. A bulge is

blown and opened with a sharp flame at the center of this seal as shown at (b). The opening is molded and a small side tube is joined to the edges of it to form a continuation of the inner section as shown at (c) and (d).

Blowing bulbs. Difficulty may be experienced in making large bulbs (of 2 inches in diameter or larger), for which it is necessary to heat heavy masses of soft glass to a uniform temperature in the flame. Also, the work must be skillfully managed outside the flame to make the effects of air cooling symmetrical. Because of these difficulties it is advisable to use commercial balloon flasks for bulbs rather than to make them from tubing. Small bulbs, less than 1 inch in diameter, are not so difficult to make.

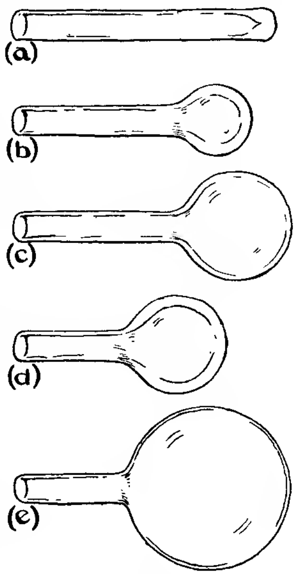

Fig. 22.

The first operation in making bulbs is to heat the end of a glass tube until the glass collects as shown in Fig. 22(a). As glass collects, it is alternately blown out and shrunk to distribute it uniformly until enough has collected for the final bulb. The collected glass is then heated to a uniform temperature and removed from the flame.

After the work has been rotated a few seconds about a horizontal axis, it is expanded by blowing through an appropriate mouthpiece. The blowing is gentle at first and stronger as the glass stiffens. The work is continuously rotated. However, if one portion of the surface tends to expand more rapidly than the other portions, it is turned down and cooled to restrain its expansion, since the under side of the work cools most rapidly.

To blow a bulb in the middle of a tube, the operation of collecting glass, as described above, is carried out in zones

until several adjacent ones are obtained as shown in Fig. 23(a) to (c). Then, by blowing and shrinking, these are combined in a single uniform zone (d). This is well heated, removed from the flame, allowed to cool a moment, and blown to the desired form (e).

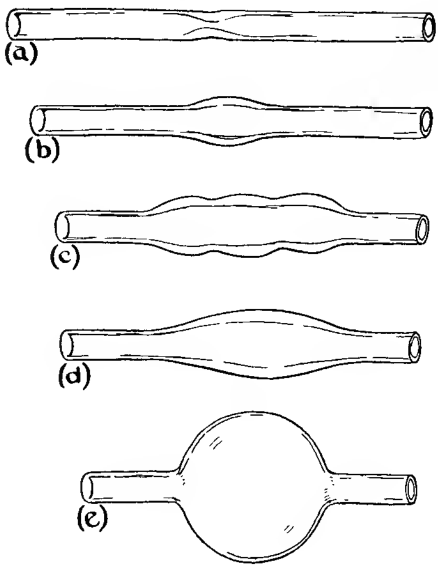

Fig. 23.

Constrictions. Two types of constrictions may be required. One, useful for preventing kinetic overflow of mercury in a manometer tube when the pressure suddenly changes, has a constricted inner wall but uniform outside diameter. The second type, useful as a "seal-off" for a vacuum system, has a uniform wall thickness. To make either type, the glass tubing to be constricted is heated and worked until the glass walls thicken. This operation is essentially the same as the preliminary operation for blowing a bulb in the middle of a tube as shown in Fig. 23(a). After the walls have been thickened, the glass is removed from the flame, and the tube is rotated and pulled instead of blown as for a bulb. To get a constriction of the first type, the tube is pulled until the outside diameter of the tube is uniform, while to get a "seal-off" constriction the tube is pulled until the wall thickness is uniform.

Correction of errors. Owing to errors of manipulation, the walls of glass apparatus frequently are not uniform. This lack of uniformity not only detracts from the workmanlike appearance of the finished apparatus but also increases the difficulty of annealing, since the thick and thin portions

tend to cool at different rates, a circumstance which causes strain in the glass.

Excessive glass can be drawn off from a region in the walls of an apparatus by using a piece of cane as illustrated in Fig. 13(a). After the required amount of glass is drawn off, the region is worked by blowing and shrinking until the wall thickness becomes uniform. Also, if the wall of a region is too thin, glass can be added from a piece of cane and worked out smooth by blowing and shrinking. Holes may inadvertently appear in the work. They are closed by drawing their edges together with a piece of cane.

Platinum seals. Formerly, the only satisfactory method of making a metal-to-glass seal was by the use of platinum and soft glass. Such seals are rarely used now because of the high price of platinum. Also, hard glass, which seals directly to tungsten, is now used extensively for making laboratory apparatus. However, a platinum tube may be required to introduce pure hydrogen by diffusion into a glass apparatus. For this and other special purposes, platinum–soft glass seals are required.

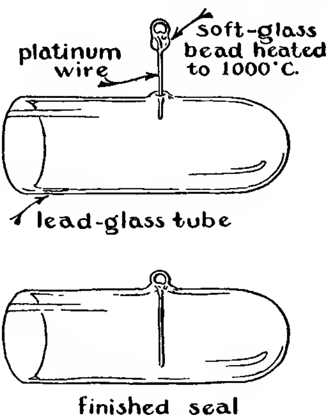

Fig. 24.

Fig. 24 shows a platinum electrode in a soft-glass tube. In making this platinum seal, a small bead of soft glass (either lead or soda glass) is first fused to the platinum wire. The bead and wire are heated to about 1000° C. to obtain a good glass-to-metal bond. Then the bead is sealed into the wall of the tube as shown in the illustration.

Tungsten-glass seals. Tungsten wires may be sealed through Pyrex if their diameters are less than 0.060 inch. Larger tungsten wires, to diameters of twice as much, are first sealed in a sleeve of Nonex glass, which in turn is sealed

into the wall of glass apparatus. This latter operation is necessary, especially if the seal is to be exposed to the heat of a baking-out oven. Nonex glass has a lower softening temperature than Pyrex, and between the strain point and room temperature the total thermal expansion of Nonex is almost equal to the expansion of tungsten for the same temperature interval.

A tungsten wire is prepared for sealing through glass by heating it to a white heat in the gas flame. If this is not done, bubbles appear at the surface of the seal. The surface of the tungsten is cleaned for sealing by heating and touching it with a piece of potassium or sodium nitrite. The tungsten is then washed, and a short sleeve of Pyrex (or Nonex, depending on the size of the wire) tubing is fused to it as shown in Fig. 25(a). The intense heating required to shrink the glass should be started at one end of the sleeve, so that the shrinking progresses from that end. This avoids trapping air bubbles between the metal and the glass. The interface between glass and tungsten is red, because oxide on the surface of the tungsten dissolves in the glass and dyes it. After the sealing operation between glass and metal is finished, the sleeve is welded into the apparatus as shown at (b). In making metal-to-glass seals, it is important to cool the glass slowly to avoid excessive strain.

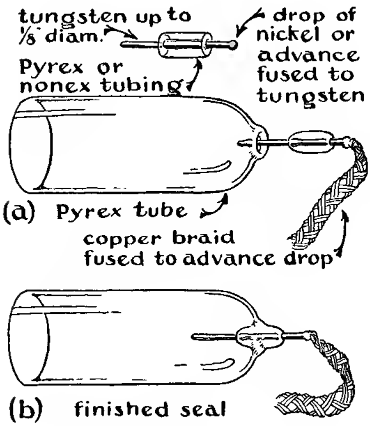

Fig. 25.

Tungsten wire is frequently fibrous, having longitudinal channels which may leak if it is sealed into a vacuum apparatus. To avoid such a possibility, the tip of the tungsten should always be closed by fusing nickel or advance wire over it. The nickel or advance tip also affords a place

for attaching copper wires. Copper can be fused to these tips, whereas it cannot be easily welded to tungsten directly.

Discharge tube electrodes are made from coiled aluminum wire of about $\frac{3}{32}$ inch in diameter and a tungsten-Pyrex seal as shown in Fig. 26. The aluminum-wire projection of the coil is fused to make the connection to the tungsten wire. The tungsten wire with a nickel enlargement to secure it in

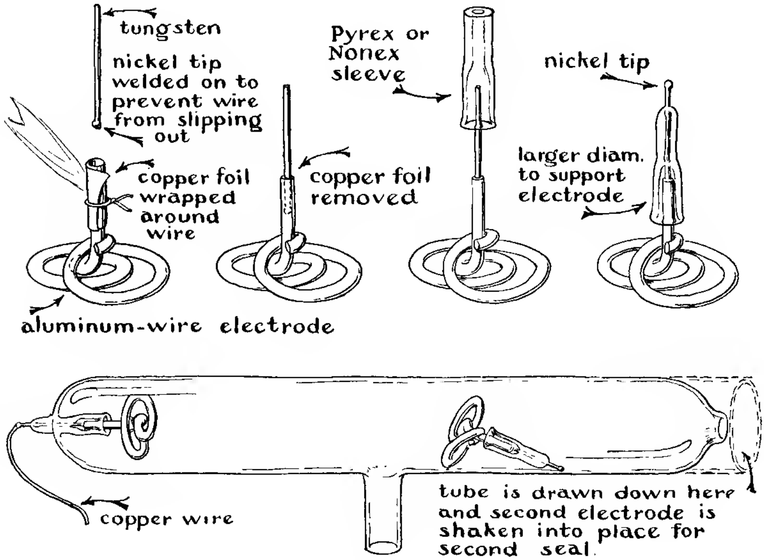

Fig. 26.

position is pushed into the fused aluminum. The projection is wrapped with copper foil to preserve its form. After the aluminum has solidified, the copper foil is removed. A glass sleeve, shaped as illustrated, is then sealed to the tungsten. This sleeve fits the aluminum projection and affords additional support for it.

Copper-to-glass seals. It is possible to seal copper to Pyrex or soft glass by the technique developed by W. G. Housekeeper.[2] The copper has a much larger coefficient of thermal expansion than either type of glass—it is the arrangement

[2] Housekeeper, W. G., *Elect. Engineering*, *42*, 954 (1923).

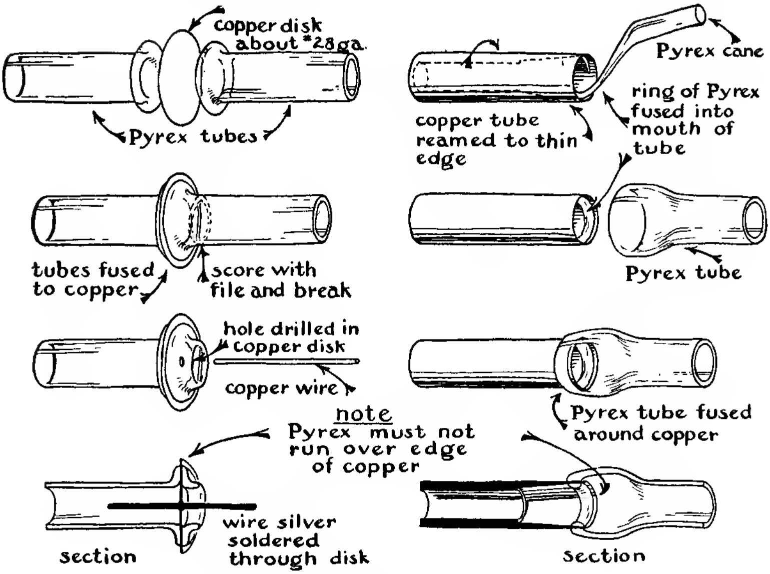

Fig. 27. Housekeeper glass-to-metal seals.

of the seal which prevents the glass from breaking. When the copper is thin, it is deformed to absorb differences between its expansion and that of the glass, a circumstance made possible by its high ductility and low yield point. The construction details of various seals developed by Housekeeper are shown in Figs. 27 and 28. For the constructions shown in Fig. 27 it is important to prevent the glass from passing over the rim of the copper.

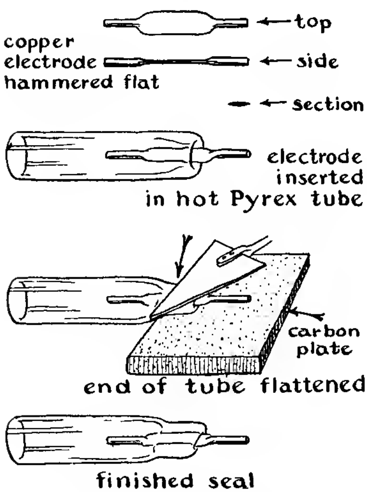

Fig. 28. Housekeeper seal.

The seal shown in Fig. 28 is made with a copper wire, which is hammered out to have thin sharp edges. Care is necessary in heating the Pyrex to avoid melting the copper.

Kovar and Fernico.[3] The rate of expansion of glasses increases near their softening temperatures, as Fig. 4 shows. On the other hand, the thermal expansion for most metals is nearly linear. However, the expansions of two new alloys, Kovar and Fernico, closely duplicate the expansion of some of the commercial glasses.[4] These alloys yield metal-to-glass seals which are unstrained under all annealing conditions, and they may be sealed to appropriate glasses without any of the special procedure required for Housekeeper seals. Large seals of 4 inches in diameter and $\frac{1}{8}$ inch in wall thickness have been made between Kovar and 705 AJ glass. Such seals as the ones shown in Fig. 29 have made modern all-metal radio tubes possible.

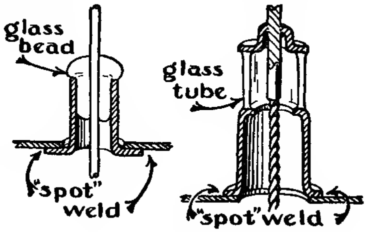

Fig. 29.

[3] The fundamental study of expansion properties of Fe-Ni-Co alloys, on which this kind of metal-to-glass seal is based, was made in the Westinghouse Research Laboratories by Howard Scott, Technical Publication 318, American Institute of Mining and Metallurgical Engineers (1930). These alloys are manufactured under U. S. Patent 1,942,260, held by the Westinghouse Electric and Manufacturing Company. Further information is contained in Scott, Howard, *Frank. Inst., J.*, *220*, 733 (1935); Burger, E. E., *Gen. El. Rev.*, *37*, 93 (1934); and Hull, A. W., and Burger, E. E., *Physics*, *5*, 384 (1934). The Westinghouse product, called Kovar, is obtainable from the Stupakoff Laboratories, 6627 Hamilton Avenue, Pittsburgh, Pennsylvania. Fernico is obtainable from the General Electric Company, Schenectady, New York.

[4] According to A. W. Hull, "Fernico is capable of existing at room temperature in either the gamma, face-centered phase, or in the alpha, body-centered phase. When annealed from 900° or more, it has the face-centered structure and the characteristic low expansion, and is stable in this condition at any temperature above −40° C. Exposure to liquid air temperature or mechanical strain will transform it into the alpha phase, which has a different expansion and is to be avoided."

According to Mr. Scott, "To obtain the desired low and reversible expansion characteristic of Kovar and Fernico, their composition is so adjusted that transformation from the gamma to alpha phase occurs between − 80 and − 180°C. Seals, however, cannot be cooled safely below − 40°C. because of the progressively increasing expansion between metal and glass on cooling below room temperature. Special compositions can be made which make possible cooling to somewhat lower temperatures."

These new alloys may be soft-soldered, copper-brazed, and spot-welded. It is not recommended that they be silver-soldered, however, as this tends to make them brittle. They oxidize much less than iron and therefore do not oxidize seriously at elevated temperatures. Nevertheless, care should be taken to avoid extended overheating during sealing. An important property of the alloys is that they are not attacked by mercury.

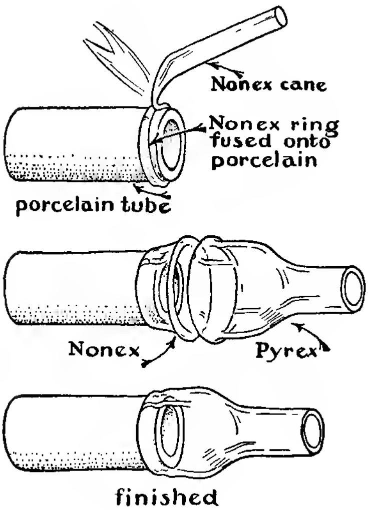

Fig. 30.

Porcelain-Pyrex seals. Porcelain, particularly the grade known as Insulite,[5] may be sealed directly to Pyrex in small diameters (less than $\frac{1}{2}$ inch), or it may be sealed to Pyrex in large diameters with an intermediary glass ring of Nonex as shown in Fig. 30.

[5] Insulite is obtainable from Stupakoff Laboratories, 6627 Hamilton Avenue, Pittsburgh, Pennsylvania.

CHAPTER II

Laboratory Optical Work

Introduction. In this chapter we will describe the technique of making the optical surfaces required for mirrors, prisms, interferometers, lenses, and so forth. The optical surfaces on these instruments are characterized by being much more accurate than ordinary machined and ground surfaces. In fact, optical tests sensitive to a few millionths of an inch are necessary to show their lack of true perfection. Since our concern here is with high-precision work, in which errors are usually less than a wave length of light, we do not include methods used for plate glass, cheap lenses, and other commercial work in which the tolerance is greater.

The technique described here is intended primarily to guide the research worker who finds it desirable or necessary to prepare his own optical surfaces.

In any case the task set before the worker is that of generating an extremely accurate polished surface. Accordingly, we will first set down the general technique involved without detailed reference to what is being made. Later we will treat of special procedures.

General procedure. The glass or other material on which the optical surface is to be prepared is first roughly formed to the desired shape. For example, in the case of a lens, the first step will consist of cutting out a disk of glass. A prism will be first sawed or ground to rough dimensions from a larger block. The proposed surface itself is then generated more precisely by periods of grinding with suitable laps. The surface is ground first with coarse grits of Carborundum to conform approximately to the specifications. Then finer and finer abrasives are used until at last the grinding is terminated with the finest emery flour. The grinding is

periodically interrupted for testing with a straightedge, template, micrometer, or spherometer. After fine grinding, the surface is polished with a pitch lap and rouge. Finally it is brought as near to perfection as the specifications require by "figuring," that is, by local retouching with polishing tools. The figuring is guided by delicate optical tests.

Theory of grinding and polishing. Optical grinding and polishing are alike in that both require the use of a material which is harder than the glass. This material is used in the form of loose grits or fine powder. The two operations are unlike in that the grits and powder used for grinding are worked over the surface with a hard tool, ordinarily made either of glass or cast iron, whereas polishing tools are made from a soft base material. A polishing tool for preparing precise optical surfaces is usually composed of some combination of pitch and wax as the soft base material. Paper cloth and wood are often used for polishing tools in cases in which no great precision is demanded.

The grinding process depends upon the characteristic conchoidal fracture produced when an excessively high pressure is applied to a point in the surface of the glass.

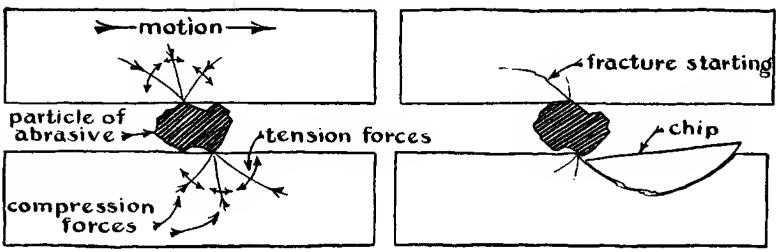

Fig. 1.

The pressure exerted on the surface by a single particle of abrasive or grit, as it is rolled about between the tool and the work, builds up stress beyond the strength of the glass, resulting in the removal of a chip. This is illustrated by Fig. 1. Carborundum and emery grits are ordinarily used. The efficiency of the process depends primarily on the sharpness of the grits. Carborundum grits break down faster

than emery, although they are harder than emery. Fractured Carborundum grits have sharp edges and consequently they grind fast. Ellison[1] says that Carborundum grinds about six times as fast as emery. Carborundum is used for the first coarser grades of grits, and emery for the last finer grades. Natural emery (corundum) cuts about twice as fast as synthetic emery. The corundum produces a smoother surface than either Carborundum or synthetic emery and is, accordingly, best for the final grinding.

The hardness of various abrasives is indicated in Moh's extended hardness scale. (See Table I.)

TABLE I

HARDNESS SCALES

Moh's Scale of Hardness		Extended Moh's Scale	
Substance	Value	Substance	Value
Orthoclase	6	Orthoclase or periclase	6
Quartz	7	Vitreous pure silica	7
Topaz	8	Quartz	8
Sapphire	9	Topaz	9
Diamond	10	Garnet	10
		Fused zirconia	11
		Fused alumina	12
		Silicon carbide	13
		Boron carbide	14
		Diamond	15

Ridgway, R. R., Ballard, A. H., and Bailey, B. L., "Hardness Values of Electrochemical Products," a paper presented before the Electrochemical Society, May, 1933.

From a practical point of view, we may consider that the polishing operation is a planing process.[2] The grains of

[1] Ingalls, Albert G., editor, *Amateur Telescope Making*, page 74. New York: Scientific American Publishing Company, 1935.

[2] For a more comprehensive treatment of the theory of polishing from a different point of view, see the following:

Lord Rayleigh, *Proc. Opt. Convention*, No. 1, page 73 (1905); and *Scientific Papers*, Vol. IV, page 542. Cambridge: The University Press, 1903.

French, J. W., "The Working of Optical Parts," *Dictionary of Applied Science*, Vol. IV, page 326. London: The Macmillan Company, 1923.

Finch, G. I., "The Beilby Layer," *Science Progress, 31*, 609 (1937).

abrasive appear to fix themselves automatically in the soft material of the tool, usually pitch, so that their crystal surfaces are parallel to the direction of motion of the tool and parallel to the plane of its surface. Thus a complex scraper is formed. As this moves over the glass, the height of each abrasive particle is automatically adjusted in the soft backing so that it produces a fine smooth cut. The removed glass is washed away by the liquid lubricant, usually water. The planing action starts on the peaks of the "hills" that result from the fine grinding and produces a full polish there at the first stroke. Continued operation of the polishing tool removes additional glass, so that the hills become plateaus and are finally planed down to the level of the deepest valleys. The character of the surface on any particular plateau is not improved by continued polishing—it is to be regarded as fully polished from the first stroke. This is illustrated in Fig. 2. After the whole surface becomes uniformly polished, further working with the polishing tool removes additional glass. In constructing an experimental aspheric camera lens, as much as thirty thousandths of an inch of glass has been removed by polishing.

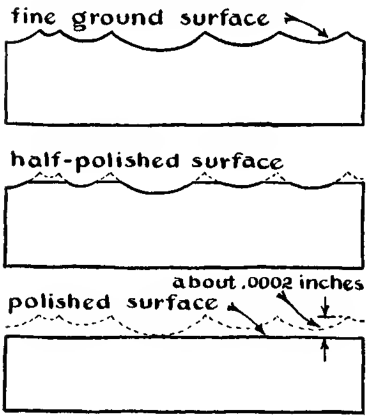

Fig. 2.

Methods of polishing. Glass can be successfully polished with almost any fine abrasive, provided a suitable soft and yielding backing is used. For some types of work—for example, for edging mirrors where irregularities in the surface do not matter—glass is polished with a wood tool charged with Carborundum or emery. Glass may be polished with rouge, either the red oxide or the magnetic black oxide, and also with charcoal or oxide of tin. However, for

ordinary optical work rouge is the most satisfactory polishing material. Surfaces of glass, quartz, speculum metal, calcite, and fluorite are best polished with rouge on a wax or pitch tool. The action of various polishing agents depends on the type of backing, whether cloth, paper, or pitch is used, on the hardness of the material being polished, and on the method of lubrication. Some agents which are indifferent polishers when used with a wax or pitch tool and lubricated with water are quite effective when used dry on a paper lap. For paper polishing, oxide of tin (putty powder) is commonly used. Chromium oxide (Cr_2O_3) is recommended for polishing certain metals such as stainless steel which are "attacked" by rouge.

The material for the polishing tool may be a soft metal—copper, lead, or aluminum. Tools made of these metals are sometimes used for polishing thin specimens of minerals which are to be examined with the microscope. Levigated alumina is usually employed as abrasive for work of this type.

The polishing tools used in precision optical work are made of pitch or pitch and wax compounds, in contrast with cloth- or paper-faced tools used on some commercial products. Glass is polished with surprising rapidity on a cloth polisher, but it exhibits a peculiar grainy "lemon-peel" surface. This method of polishing is generally used in the manufacture of plate glass. Paper polishers in general produce a somewhat better surface than cloth but are seldom used except for the manufacture of inexpensive lenses, such as for cheap hand magnifiers and so forth. All polishing tools of a fibrous nature produce a "lemon-peel" surface.

Procedure for optical surfaces of 3 to 6 inches in diameter and larger. The technique which will form the nucleus of our first treatment is particularly suited to the making of surfaces of 3 to 6 inches in diameter or larger worked in glass or quartz. The procedures involved are fundamental and apply equally to mirrors, lenses, or prisms. The method treated here is used by D. O. Hendrix, a practicing

optician associated with Mount Wilson Observatory.[3] This procedure is different in some respects from that described in the classic book on amateur telescope making by Ingalls, Porter, and Ellison.[4] For example, in their book they recommend using the tool underneath the work, while here we treat primarily of the method using the tool on top of the work.

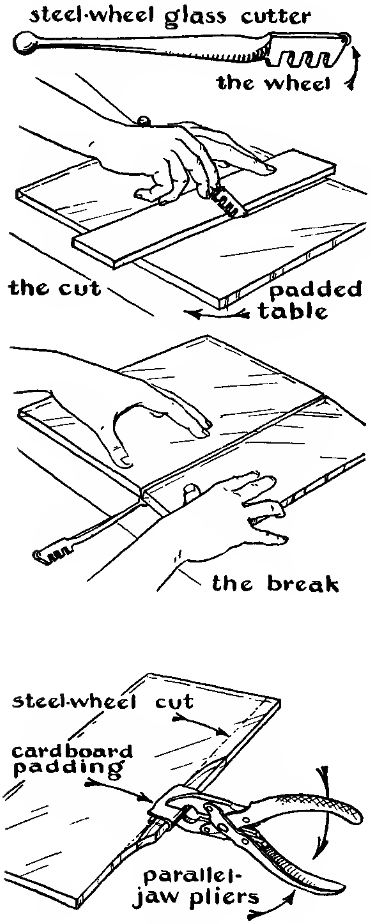

Fig. 3.

Cutting and roughing out the work. The work, whether it is a mirror, a lens, or a prism, can often be cut to rough shape from stock plate glass with an ordinary wheel cutter, the most common form of glass cutter, which is used for cutting all kinds of polished glass in all ordinary thicknesses. The cutter is drawn across the glass surface once with sufficient pressure definitely to mark the glass. It should not be run back and forth along the same line. After the glass is "marked," it is broken by bending it away from the cut, as shown, for example, in Fig. 3. The parallel-jawed pliers, also illustrated in Fig. 3, are useful for making narrow cuts. The break may also be started by lightly tapping the glass on the back side opposite the mark

[3] I am indebted to Mr. D. O. Hendrix for the procedures presented here.

[4] Ingalls, Albert G., editor, *Amateur Telescope Making, Advanced.* New York: Scientific American Publishing Company, 1937.

with the small knob provided on the handle of the wheel cutter.

The procedure for cutting thick plate glass is to lubricate the wheel cutter with turpentine or kerosene before the cut is made. After the glass is marked, the break is started with a blunt chisel. The chisel is held firmly against the back of the glass at a point directly opposite the mark and tapped sharply with a small hammer. The edge of the chisel should be parallel to the mark. It is well to have the glass supported, cutter-mark down, on a cloth or padded surface. When the break has started, it is led along the cut with the chisel. (See Fig. 4.)

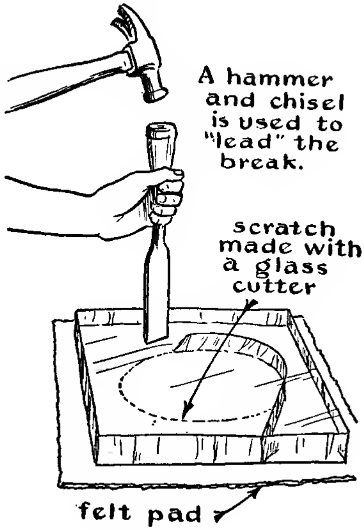

Fig. 4.

Very thin glass is best cut with a diamond point especially mounted and sharpened for this purpose.[5]

If a disk is desired, the glass is first cut square, and the corners are then cut to give a polygonal piece approximating the desired shape. The rough edges may be removed by holding the glass against a rotating flat disk of cast iron fed with a mixture of Carborundum and water. (See Fig. 5.) Also,

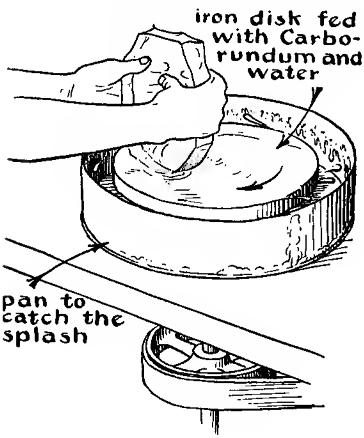

Fig. 5.

[5] Diamond glass cutters may be obtained from the Standard Diamond Tool Corporation, 64 West 48th Street, New York City. This company also sharpens diamond glass cutters.

the glass disk may be waxed onto a metal plate mounted in the headstock of a lathe. As it is rotated, the edges are ground with an iron tool, which is fed with Carborundum and water as shown in Fig. 6. A light springy tool is recommended. Oilcloth should be used to protect the lathe so that abrasive does not get into its working parts or on its ways.

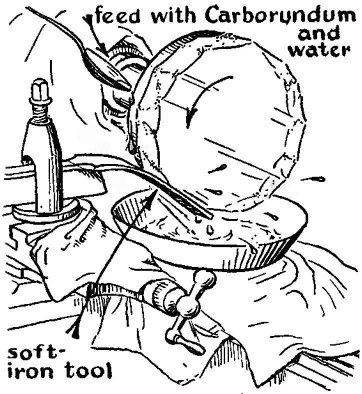

Fig. 6.

Biscuit cutter. A common method of cutting small disks (up to about 6 inches in diameter) from slabs of glass is by means of a "biscuit cutter." This is simply a thin-walled tube of iron or brass mounted in a drill press as shown in Fig. 7. The rotating tube is fed against the glass, Carborundum and water being applied with a spoon. Fig. 7 also shows a novel method of central feeding. To prevent chipping when the biscuit cutter goes through the glass, it is well to wax an auxiliary backing plate onto it with beeswax. Grade 60 or 90 Carborundum should be used except for fine cuts or cuts on delicate and fine work, in which case grade 120 Carborundum should be used. The cutter will cut more rapidly if instead of water a mixture of turpentine and camphor is used with the Carborundum. The proportions of the mixture should be 5 grams camphor to $\frac{1}{2}$ liter turpentine.

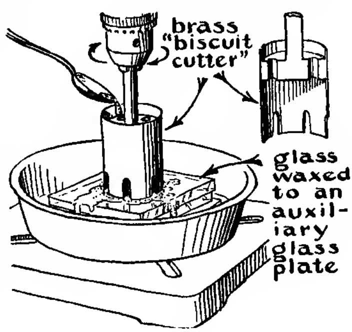

Fig. 7.

Diagonal mirrors, such as the Newtonian diagonal for a small telescope, may be cut out of a larger figured flat mirror with the biscuit cutter. The larger mirror is mounted in the drill press at an angle of 45° and cemented with beeswax on a backing of plate glass. It is cut in the manner shown in Fig. 8. Usually the front of the flat is also coated with a cover glass, stuck on with beeswax, to prevent scratching the figured surface with the abrasive. A mirror thus cut out may develop a slight turned-up edge. However, if the cut rim, which now has a rough ground surface, is polished with wood and Carborundum, the figure of the mirror will usually become flat again. (This is sometimes called the Twyman phenomenon.)

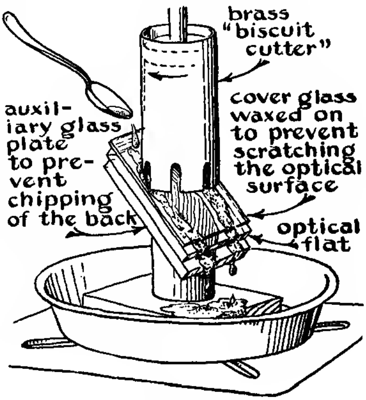

Fig. 8.

Glass saws. Strips and slabs of glass are cut from a thick piece of glass stock with saws. The simplest and easiest of these to set up is the so-called "mud saw," shown in Fig. 9(a). It consists of a rotating disk of soft sheet iron fed with a mixture of Carborundum and water. Sometimes sugar, syrup, talc, glycerin, or bentonite (particularly good) is added to this mixture to make the Carborundum adhere to the blade and to keep the grits from settling out in the reservoir pan. The usual construction allows one edge of the saw to dip into the "mud," or Carborundum mixture, which is held in a pan below the disk. The work to be slabbed is supported on a counterbalanced table and is held against the saw with a slight pressure.

A diamond saw forms an efficient slabbing cutter. The diamond saw shown at the bottom of Fig. 9 may be made as follows: The diamonds are pulverized as shown at (b) and charged into the nicks of a circular disk prepared as shown

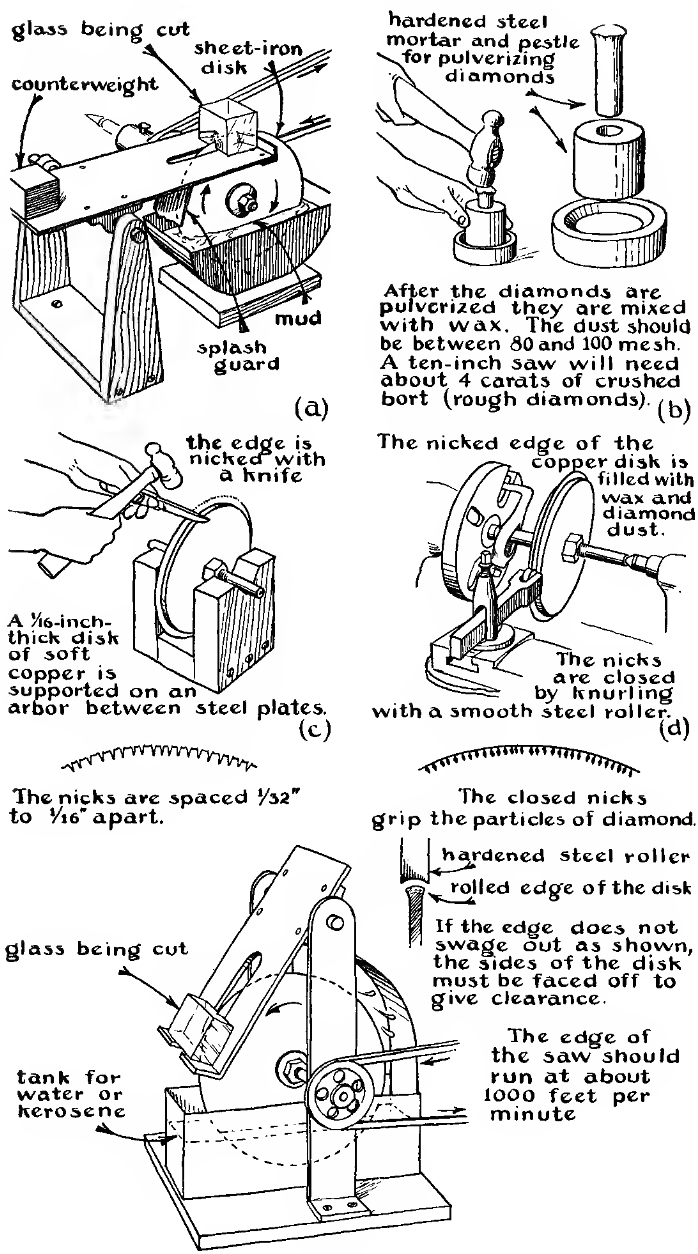
glass being cut
sheet-iron disk
counterweight
mud
splash guard
(a)
hardened steel mortar and pestle for pulverizing diamonds
After the diamonds are pulverized they are mixed with wax. The dust should be between 80 and 100 mesh. A ten-inch saw will need about 4 carats of crushed bort (rough diamonds).
(b)
the edge is nicked with a knife
A 1/16-inch-thick disk of soft copper is supported on an arbor between steel plates.
(c)
The nicked edge of the copper disk is filled with wax and diamond dust.
The nicks are closed by knurling with a smooth steel roller.
(d)
The nicks are spaced 1/32" to 1/16" apart.
The closed nicks grip the particles of diamond.
hardened steel roller
rolled edge of the disk
If the edge does not swage out as shown, the sides of the disk must be faced off to give clearance.
glass being cut
tank for water or kerosene
The edge of the saw should run at about 1000 feet per minute

Fig. 9.

at (c). These nicks are rolled as shown at (d) to hold the diamond powder and give the saw clearance. In operation the saw blade is lubricated and washed with water or kerosene.

Modified Draper machine. Once the prism, lens, mirror, or other blank is cut out, the operations involved in grinding the curves and polishing and figuring them may be carried out either by hand or with a grinding and polishing machine. A machine like the one shown in Fig. 10, a so-called modified Draper machine, is suitable.

The tool is moved laterally by the modified Draper machine in a thin oval stroke across the face of the work. The amplitude of this stroke is controlled by adjustment of the throw of the crank. The stroke can be arranged by movement of an adjustable guide so that it is either diametral or chordal in respect to the work. The tool may be allowed to rotate freely, or it may be driven by a belt. Also, the tool may be loaded to increase its pressure, or it may be counterbalanced to decrease its pressure on the work. The table on which the work is mounted is power driven to rotate about 2 r.p.m.

Support of the work. It is very important to support the work properly, or it will develop astigmatism, the anathema of optical work.

The first requisite is to have the modified Draper machine table turned and lapped 0.001 to 0.003 inch concave, depending on the size. It is then covered with a layer of thin felt and oilcloth as shown at the bottom of Fig. 10. This supports the glass uniformly on its flat bottom side and effectively prevents flexure during all of the operations. When the second surface of a lens is being worked, the plane concave glass tool that was used in the fine grinding of the first face is used to support the work on the grinding table. The tool is first mounted on the table concave side up. Then it is covered with felt and the lens is laid on it.

The work is supported laterally on the table by three edge arcs, which should fit neatly to the edge of the blank without

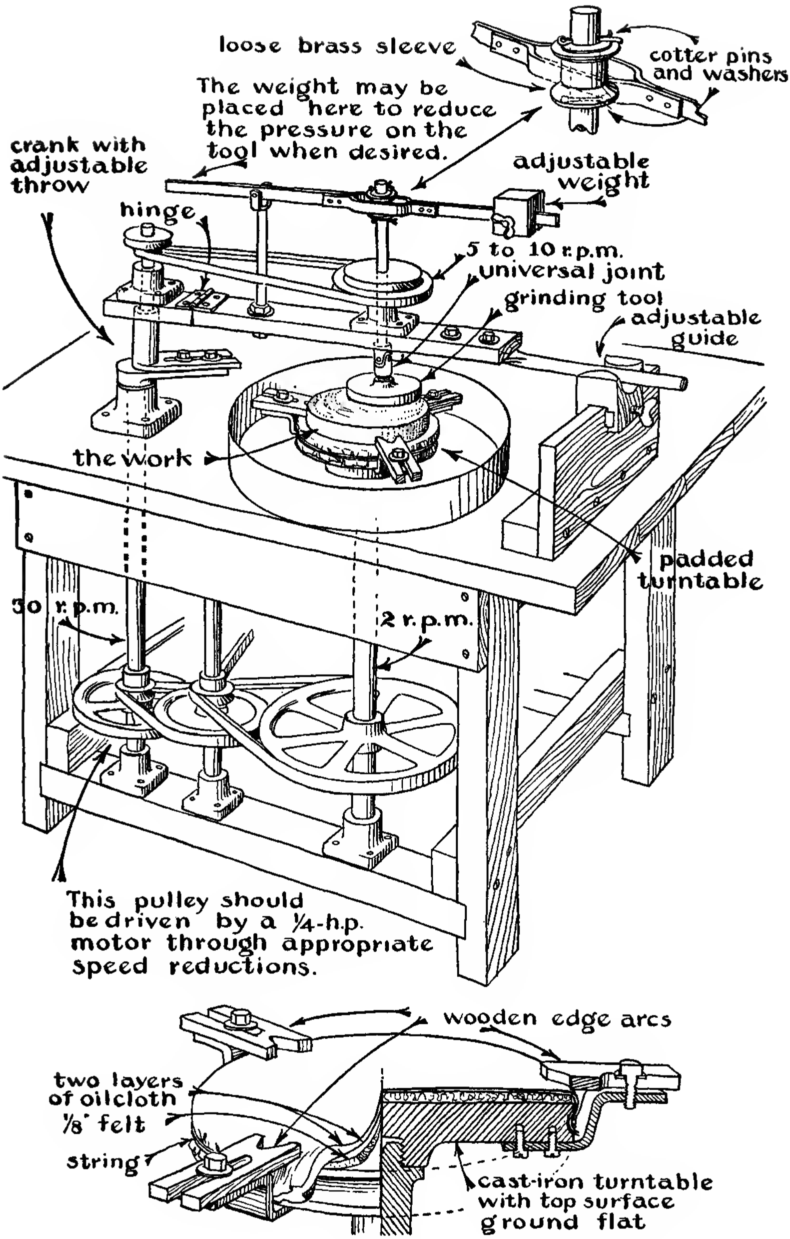

Fig. 10. Note that the universal joint shown here is used only for rough grinding. For fine grinding and polishing, the tool is connected to the crossarm by a pivot and socket arrangement. See Figs. 16 to 20.

exerting any pressure on it except as is necessary to balance lateral forces produced by the action of the tool. The work is moved around in the edge supports from time to time during grinding and polishing to distribute the effect of these forces uniformly around the periphery of the mirror, to avoid the introduction of astigmatism.

The work, if it is a mirror or lens, is prepared by having its face and back fine-ground and made parallel with a rotating cast-iron lap used with loose grits as shown in Fig. 5. The edges are then ground round and lightly beveled. Finally, the edges are polished with a wood tool and fine Carborundum grains.

Grinding the curve in the work. Full-size grinding tools of tough metal such as copper, brass, or soft iron, when turned to a definite radius of curvature, will reproduce this radius in the glass. The soft metal surface becomes charged with abrasive and is not worn appreciably when it is used on a brittle material such as glass. On the other hand, cast-iron tools change slowly during grinding, and glass tools change at approximately the same rate as the work.

The traditional way of making a 6-inch mirror by hand is to use two equal disks of glass, one as the work and the other as a grinding tool. The grinding is accomplished as shown in Fig. 11 with the work mounted on a firm pedestal, the height of which is optional. The optician walks around it as he strokes the work with the tool. Pressure is applied to the center of the tool with the thumb of the right hand. The tool is rotated with the fingers in a counterclockwise direction as it is stroked across the right side of the work. When a chordal stroke is used, the upper disk becomes concave and the lower convex. By this means a certain amount of control is given the operator. He may continue grinding, increasing the curvature in the surfaces all the time, until the desired result is attained. If he wishes to decrease the curvature, he will place the tool below and stroke it with the work. Or he may periodically reverse the relative positions of the two disks if he wishes to hold the surfaces

fairly flat or constant in radius of curvature. When it is desired to hold the curvature constant, a diametral rather than a chordal stroke is used.

On the modified Draper machine, the grinding of a mirror to a definite radius of curvature is effected with a small tool.

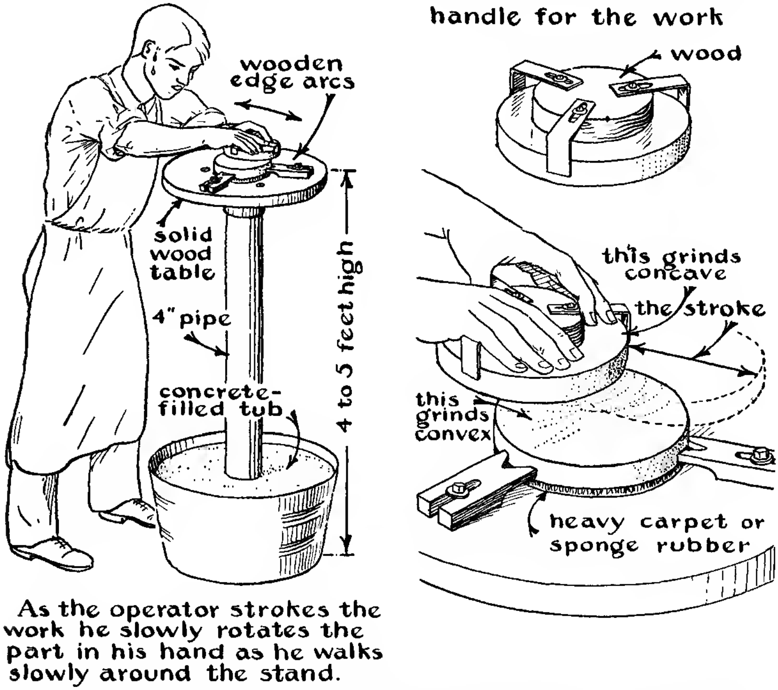

Fig. 11. Many workers will prefer to have the work at a lower level, 3 to 4 feet, than is shown here. Note: The operator shown in this figure is left-handed.

Concave curves are cut in the glass with a $\frac{1}{3}$-size tool stroking the work across its center. A convex curvature is generated by a sub-diameter tool stroked across a chord of the work. Although a convex curvature will be generated if a full-size tool is stroked across the center of the work (diametral stroke), it becomes convex more rapidly when a chordal stroke is used. The rate at which the curvature changes is proportional to the amplitude of the diametral stroke or the offset of the chordal stroke.

After the work has been roughed out to the proper radius of curvature with 90, or for extreme curves 60, Carborundum, the full-size tool is used to true up the surface. The stroke used here is a thin oval across the center of the work. The amplitude used is about one third to one sixth the diameter of the work. The grinding is continued with the full-size tool until the tool and work are spherical. This is indicated by the quality of the fit between the tool and the work, which can be tested with a pencil mark made on the work. This procedure may produce scratches. A circular template is often made of the required radius and the work is ground until it fits this template. Spherometers are also used to test the work for sphericity. When the work is spherical, the spherometer reading, d, the radius of curvature of the work, R, and the radius of the circle containing the spherometer legs, r, are related as follows:

$$d = \frac{r^2 + d^2}{2R}.$$

The spherical surfaces obtainable by grinding are so good, in fact, that opticians who worked before testing methods were developed as they are today hesitated to polish the grinding pits entirely away, since they formed a convenient "landmark" to which to refer the figure.

To grind deep curves like those required for an $f/1$ Schmidt camera, one puts a band around the edge of the mirror and covers its face with a layer of Carborundum grits. The band holds the grits on the mirror. As the work slowly rotates, a fast rotating sub-diameter cast-iron ring tool is reciprocated diametrically, or nearly so, across its surface in a thin oval stroke. The amplitude of the stroke is adjusted so that the ring tool comes to the edge of the work at the extremes of the stroke.

Final grinding in all cases should be carried out with a glass grinding tool. Glass is used rather than metal in order to have the tool change at approximately the same rate as the work, thus insuring a more perfect fit at all times between

the tool and the work. The tool may be a glass disk formed as a complement of the work; that is, if the work is a convex spherical surface of radius R, the tool will be a concave sphere of almost exactly the same radius. Or the tool may be a plate of glass cemented to a metal backing. It is well to cut the grinding tool with one or more decentered grooves as shown in Fig. 12 in order to prevent suction, facilitate the access of grinding compound to all parts of the tool, and insure that the tool grinds slightly faster than the work. These grooves may be cut into the glass with the diamond or mud saw.

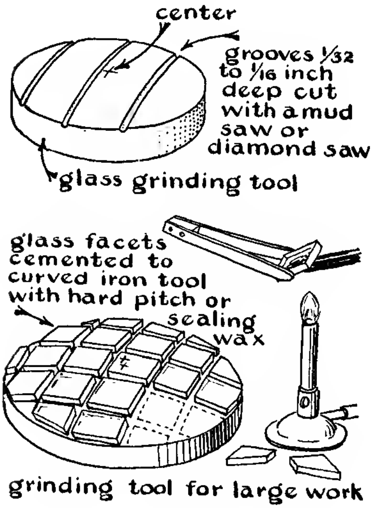

Fig. 12.

For large mirrors, glass disks or squares can be cemented to a convex or concave iron backing as is illustrated in Fig. 12.

The radius of curvature of the work, R, is determined by means of a spherometer or more simply by a template cut from metal. The latter can be cut with a sharp steel point (sharpened like a brass turning tool) mounted on the end of a board of length R and pivoted at the other end on a nail. For flats a good straightedge may be used as a template.

Fine grinding. After the proper radius is attained and the work has been trued up with the full-size tool, the optician passes successively to grades 150, F, 400, and 600 Carborundum. The full-size tool, loaded to a pressure of about 0.5 lb./square inch, is used. For a 6-inch mirror about a teaspoonful of grits is applied at a time. Each application of grits, applied with one or two spoonfuls of water, is allowed to grind until the gritty cutting sound, which is heard at first, has softened. For a 6-inch mirror, grits are

repeatedly added until the work has been ground a total time of 30 minutes (or 1 hour by hand). After a half-hour of grinding with one grade of Carborundum, the optician passes on to the next grade, and finally, after the 600 grade Carborundum, finishes with two grades of emery, $302\frac{1}{2}$ and $303\frac{1}{2}$. The work, the table of the machine, and the tool should be thoroughly washed after finishing with each grade of abrasive.

Carborundum grits as obtained commercially are well graded and do not need to be washed. However, the emeries must be washed each time they are used. The washing procedure is as follows: Put emery to a depth of 1 inch in a quart Mason jar, fill the jar with water, stir, and let settle for 10 seconds. Decant the suspended emery off to a second clean jar and discard the residue. After 10 seconds in the second jar, decant again, and repeat the operation a third time. After this, the settling time is increased to a minute to yield a residue which we will designate as residue *A*. The liquid over this is decanted into a clean jar, in which it is allowed to settle until it is clear, yielding residue *B*. The liquid over *B* is then put back over residue *A*, stirred, allowed to stand for 1 minute, and then added again to *B*. This is repeated several times to transfer a large fraction of the emery from *A* into *B*. Residue *B*, when mixed with an equal volume of powdered washed talc, is ready to be used for grinding. The talc serves as a lubricant and prevents sticking of the tool. The talc must be washed in the same manner as the emery was washed to free it of metallic iron.

The final grinding with the two grades of emery will yield a surface which exhibits specular reflection of white light at grazing incidence. At a steeper angle the reflected image is red. In fact, specular reflection of the red part of the spectrum up to a grazing angle of about 12° may be obtained. The maximum grazing angle of specular reflection affords a simple test of the quality of the fine-ground surface. A clear filament lamp should be used as a light source for this

test, and when the surface gives a reflection at a grazing angle of about 12°, the work is ready to be polished.

When it is required to have the center of the mirror perforated, the necessary hole is usually cut with the "biscuit cutter" before the grinding is started. The plug is then fastened back in place with plaster of Paris. The plug is left in place until the figuring is finished.

Pitch for tools. Polishing pitch should have the following properties: It should flow slightly at ordinary room temperature; it should trim easily with a sharp knife; and, further, it should not lose its "temper" by evaporation of volatile oils. A compound which conforms to these specifications quite well is made up as follows:

Coal tar (melting point 170° to 180° F.)	2 lbs.
Pine tar (Mefford Chemical Company)	4 liquid oz.
Beeswax	$\frac{1}{2}$–1 oz.
Venice turpentine	not more than about 2 or 3 cc.

The tar is melted and the other ingredients are added in the order listed.

The function of the turpentine is to adjust the final "temper" of the pitch. More or less turpentine is added, depending on whether a hard or soft pitch is desired. Before adding the turpentine and after each addition, test the pitch for temper. The simple method of performing this test is to chew a small sample of the pitch after chilling it by pouring it out on a cold glass surface. At body temperature, so-called "soft" pitch can be chewed, while "hard" pitch cracks under the pressure of the teeth. Furthermore, hard-pitch tools stored face up will show evidence of flow in the sides of the groove in about a week. A soft tool exhibits flow after standing a day. Polishing pitch does not attain its final hardness on cooling but continues to harden for a day or more. This is a sort of "jelling" process, which must be taken into account.

After the correct mixing temper is attained, pitch is filtered to remove small sticks or other hard particles. The hot pitch is poured through a cheesecloth filter supported on

an iron ring. Two layers of cheesecloth are adequate to hold back harmful impurities.

Polishing tools of 6 inches in diameter or less are made by simply pouring the melted pitch compound over a support to a depth of about $\frac{3}{8}$ inch. After the pitch has cooled, it is channeled by cutting it with a hot knife so that the surface is divided into a decentered system of square facets of uniform size. These facets are later trimmed in the manner shown in Fig. 13. Tools having bubbles in the pitch cause no trouble unless it happens that the bubbles occur in a definite zone on a full-size tool that is to be worked over the mirror or lens with a short stroke. In order to avoid a zone of bubbles, the pitch is cast by pouring it onto the support at one edge rather than at the center.

There are two methods of accommodating the tools to the different working conditions of summer and winter: By one, the formula is changed, the pitch being tempered with more turpentine for cooler weather; by the other, the size of the facets is changed. The facets are made smaller in cooler weather. When the formula given above is used, the facets should be about 1 inch square for temperatures above 75° F. and about $\frac{1}{2}$ to $\frac{3}{4}$ inch square for temperatures below 75° F.

If the polisher is to be used on soft or easily scratched material, such as speculum metal, it is advisable to use harder pitch and to have the facets narrow. The channels allow the pitch to flow evenly and also allow the rouge and water free access to all parts of the work. For speculum metal it is recommended that the facets be $\frac{1}{32}$ to $\frac{1}{16}$ inch wide and $\frac{3}{4}$ inch long.

To construct a polishing tool of relatively short radius, the pitch facets are first cast in a suitable mold in the form of sticks. (See Fig. 14.) These are then cut into squares and fastened to the metal tool as shown in Fig. 15.

After the tool has been faceted, it is warmed and pressed to the work, with soap in a 25 per cent glycerin solution as a lubricant on the work to prevent sticking. The pressing

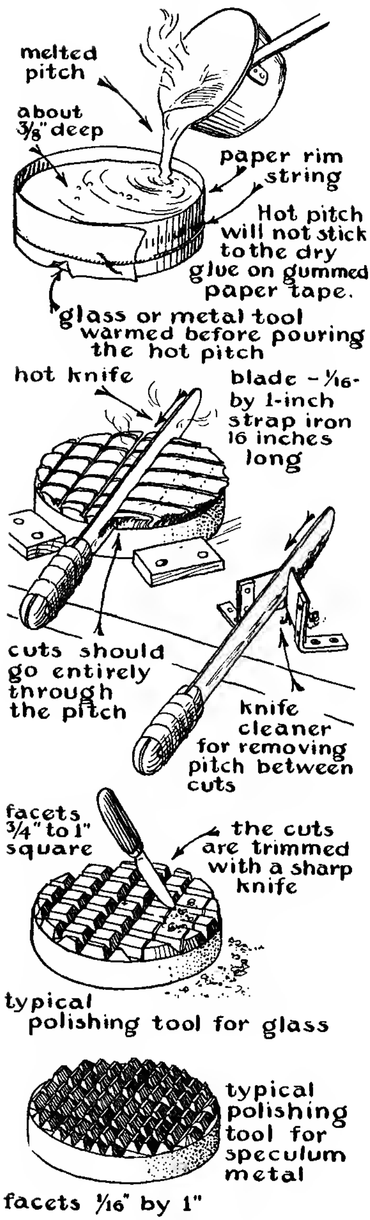
melted pitch
about 3/8" deep
paper rim
string
Hot pitch will not stick to the dry glue on gummed paper tape.
glass or metal tool warmed before pouring the hot pitch
hot knife
blade - 1/16- by 1-inch strap iron 16 inches long
cuts should go entirely through the pitch
knife cleaner for removing pitch between cuts
facets 3/4" to 1" square
the cuts are trimmed with a sharp knife
typical polishing tool for glass
typical polishing tool for speculum metal
facets 1/16" by 1"

Fig. 13.

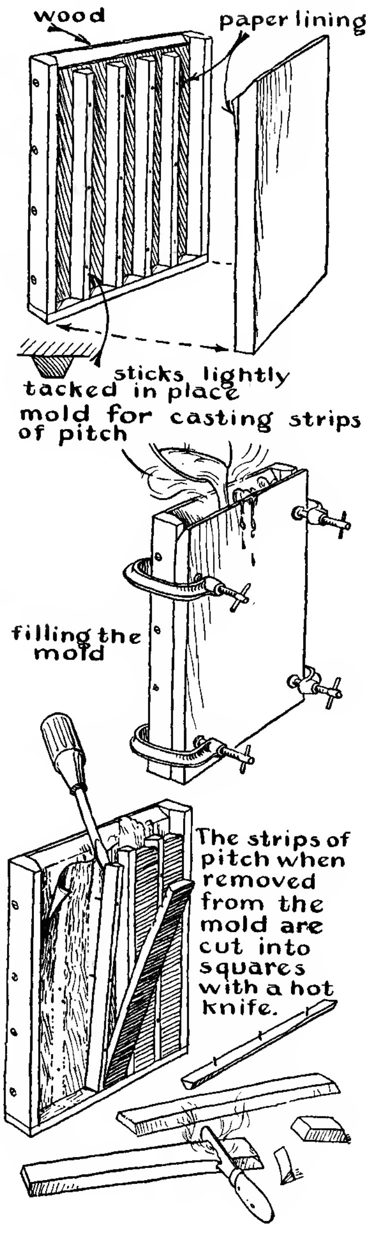
wood
paper lining
sticks lightly tacked in place
mold for casting strips of pitch
filling the mold
The strips of pitch when removed from the mold are cut into squares with a hot knife.

Fig. 14.

operation is illustrated in Fig. 16. The tool is gently warmed over a hot plate until the pitch is soft. Then it is applied to the work, wet with a mixture of soap and glycerin, and left to cool. This procedure yields an intimate contact between the tool and the work. Tools for flats may be first turned in the lathe before they are pressed. After pressing the pitch tool, it is advisable to wash it in cold water and also wash and dry the work to remove the soap and glycerin.

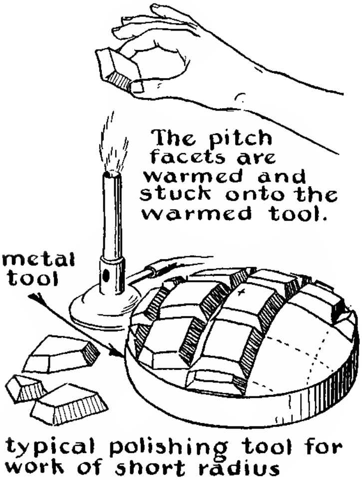

Fig. 15.

Polishing. Polishing is carried out on the table of the modified Draper machine in the same manner as grinding, except that the polishing tool is usually allowed free rotation. Rouge and water is added to the work from time to time near the edge of the tool with an

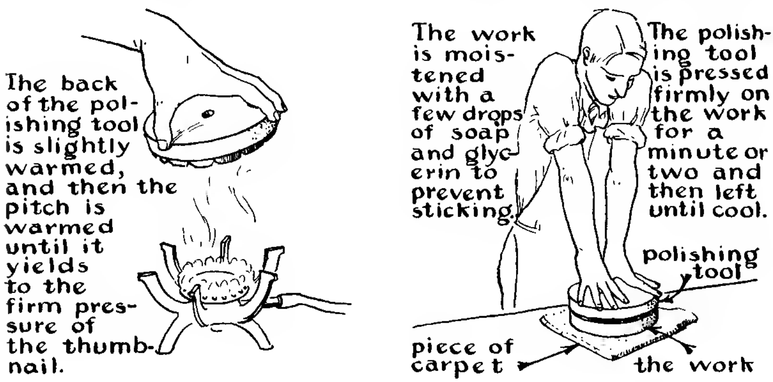

Fig. 16.

eye dropper. The rouge should be washed. The washing procedure is the same as that described for washing emery or talc, except that the settling time is longer—up to one-half hour.

Hard facets in the tool may cause sharp zones to appear in the work during polishing. To avoid the effects of such surface inhomogeneities in the pitch and resultant irregularities in the cutting action of the tool, the work is "broken up"; that is, the tool is frequently (and irregularly) given a spin. The facets in the tool should form a decentered system. A diametral stroke is employed for polishing. A feature of the polishing machine which also contributes to breaking up the work is the incommensurable coupling obtained by the belt which connects the rotation of the work with the phase of the stroke. The stroke is varied from time to time from a long stroke of one fourth the diameter of the tool to a short stroke.

If the surface of a pitch polishing tool becomes so heavily charged with rouge that it appears hard and glassy, the polishing speed will be considerably reduced, and furthermore "sleeks" are liable to appear. Sleeking, or the appearance of groovelike marks on the polished surface, is probably caused by the formation of ball-shaped aggregates of rouge, wax, and perhaps glass, which plow out shallow channels in the surface. Beeswax-coated tools are particularly bothersome in this respect. One method of avoiding sleeks is to allow the tool to run nearly dry before each application of fresh rouge. The optician calls this "drying up each wet." This probably causes the surface of the tool to become quite warm, allowing the pitch surface to flow rather rapidly and to renew itself.

Large lenses and very soft materials are best polished by coating the surface of the polisher at regular periods with fresh pitch or beeswax. The polishing tool is to be coated at intervals of 1 to 3 hours. The beeswax is applied to the facets of the tool with a swab made of cheesecloth bound on a short stick. It is advisable to have the wax smoking hot and to apply as thin a coating as possible. In polishing speculum metal, which scratches rather easily, the fresh beeswax coating is to be charged with dry rouge. The rouge is applied to the facets with the tip of the finger.

When a full polish is achieved, that is, when the grinding pits are entirely removed, the work is ready for testing and figuring. A convenient and simple test for full polish is to focus sunlight on the glass surface with a lens. The focus of this lens does not heat the glass much, but light scattered by pits in the surface is quite conspicuous if the surface is not fully polished.

To avoid introducing astigmatism into the work during polishing, it is frequently rotated a fraction of a revolution with respect to the supporting table in order to distribute the effect of edge arcs symmetrically around its periphery.

Figuring. Figuring is the process whereby a polished surface has its shape altered by local working with polishing tools. For example, a spherical surface is made aspheric, or undesirable zones or astigmatism is removed.

Sometimes in figuring plane parallels or prisms the effect of inhomogeneities in physical properties of the glass can be corrected (in first approximation) by slight deviations from flatness in the surfaces.

The general procedure in figuring is one of trial and error. Testing is alternated with local polishing on those areas which are high in reference to a desired surface.

Cutting zones and transition zones. The behavior of the polishing tool depends on its size, character of faceting, shape, and the manner in which it is manipulated on the work. There is no way in which a tool may be manipulated so that it will remove glass from a surface uniformly. Rather, each manipulation, if carried out on a perfectly flat surface, tends to produce its own characteristic zones, which will be referred to as the cutting zones of the tool. Figs. 17 and 18 illustrate the cutting zones of some typical tools. These zones are defects in the mirror surface symmetrically positioned about the center of the work. The figuring procedure consists in testing the imperfect surface and working it with a suitable tool whose cutting zones will tend to cancel the zones revealed by the test.

Sharp zones are first "softened" with a large tool coated

with soft pitch. This procedure applies both to those zones remaining from polishing and to those which may appear during the figuring. The latter are usually transition zones resulting from imperfect cancellation of a smooth zone in the work by the cutting zone of the tool. This is illustrated by Fig. 20. After the sharp zones are softened with a soft pitch tool, the optician tests again to determine the figure. To carry the figuring farther, a satisfactory surface tangent to the "valleys" of the surface, lying wholly within the glass, is imagined, and the hills relative to this imagined surface are polished away with an appropriate tool and stroke. This cycle of testing, polishing in a manner such that the cutting zones improve the figure, testing, smoothing transition zones with a soft tool, testing, and so forth, is continued, until the necessary figure is attained.

Interpretation of the action of polishing and figuring tools. If we could assign quantitative values to all of the factors influencing the cutting action of any given tool and stroke, we could conceivably predict the cutting zone for it. However, we cannot do this; but we can describe the factors qualitatively as they are appraised in the minds of opticians.

First, the polishing tool cuts away the glass in proportion to the time the tool is passing over the glass.

Second, the tool cuts faster as the speed increases. The cutting or polishing rate is not, however, proportional to the speed at which the tool passes over the work.

Third, sections of the tool which overhang the work during a part of the stroke cut relatively faster than the sections which do not overhang the work.

Fourth, the facets of the tool which lead cut faster than following facets, because new rouge available to the leading facets is wiped away from the path of following facets.

Fifth, the tool cuts fastest where the pressure on it is greatest, everything else being equal. This accounts for the selective action of the full-size tool on high zones, which action is the basis of all figuring. It is important to give this factor careful consideration in working aspheric surfaces,

in which the tool naturally works in a way that tends to return the surface to a sphere.

Figuring tools for zones. Figs. 17 and 18 show various-shaped tools and illustrate the zones which they would ordinarily produce in a true flat surface when worked with both long and short strokes. The stroke in each case is a thin oval across the center of the work. The use of an oval stroke has an advantage over a straight reciprocating stroke in that the tool never comes to a complete stop.

It will be noted from Fig. 17 that the full-size tool makes the work more convex by an amount which increases with the length of the stroke. Intermediate-sized tools, as the $\frac{5}{6}$ size, hardly change the over-all curvature of the work when a long stroke is used, while a short stroke with this tool makes the work more concave. Smaller tools make the work more concave.

It will be further noted that the effect of the tool in changing the over-all curvature is (except for the case noted) greater than its effect in producing cutting zones. This change of curvature is generally inconsequential, except where one is making flats or striving for a radius of curvature specified to extreme precision.

Fig. 18 shows the action of ring and star polishing tools.

The behavior of tools on short radius curves may differ considerably from their behavior on flats. Figs. 17 and 18 refer to flats.

As testing methods are not very precise and the polishing methods even less so, it is well to approach the desired surface carefully and slowly, with periods of polishing interrupted frequently for testing. This allows one continually to change the "stratagem according to the tactical situation and nature of the terrain."

One should use a clock to time the work done with a given polishing tool. If a mirror is improved by a certain treatment of 20 minutes' duration and the test shows that about as much more work is required, it is advisable to continue the treatment for 10 or 15 minutes more and test again in

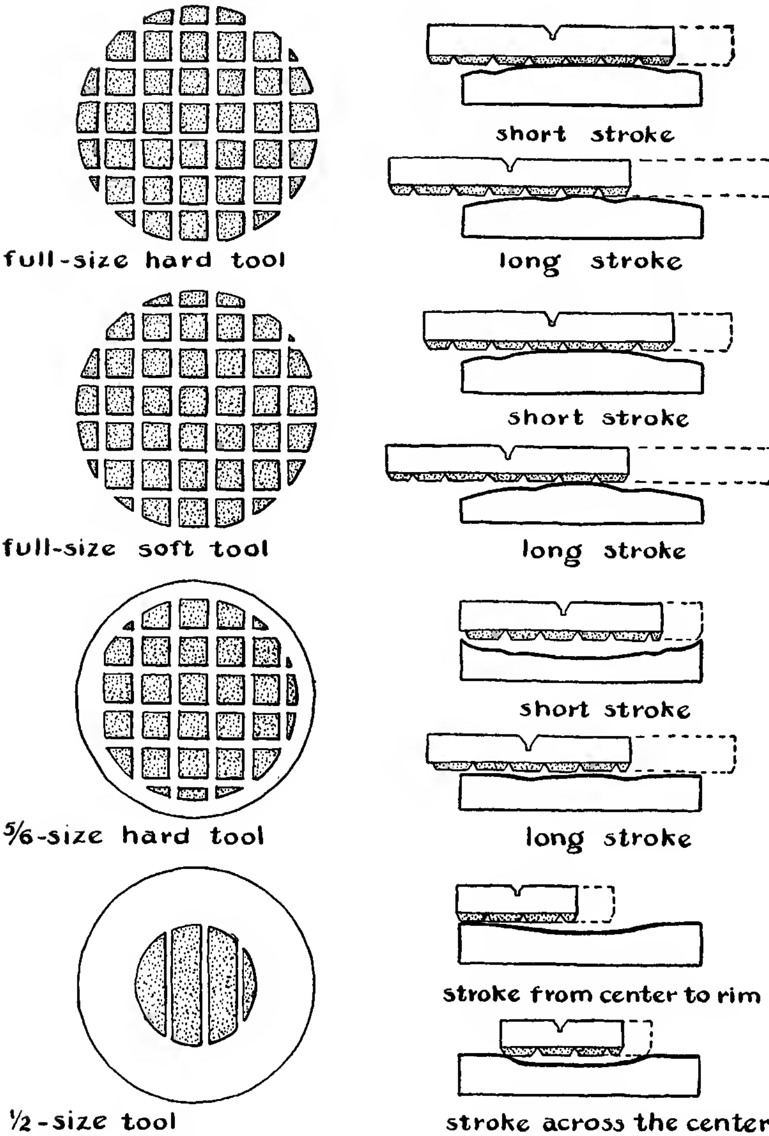

Fig. 17. Cutting zones for various tools.

order not to overreach the desired result. It must also be emphasized that tools may cut faster at first than later, so that the significance of the time factor should not be taken too seriously. Also, the behavior of any given tool may be erratic. It is best to try it for short periods at a time with frequent testing in order to be certain of its action. Inas-

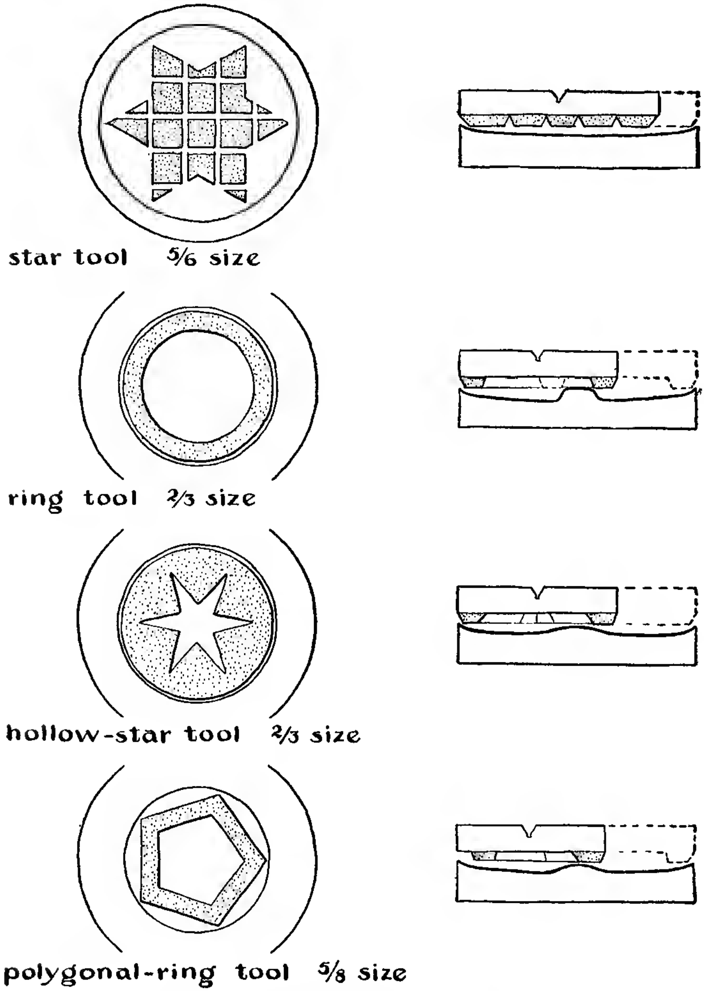

Fig. 18. Cutting zones for various tools.

much as the figuring procedure should not be hurried, beeswax-coated tools, which polish about three times as fast as uncoated tools, are not used for figuring. During the final stages of figuring, when delicate testing is required, the work should be allowed to stand on the testing support for sufficient time to allow complete equalization of temperatures.

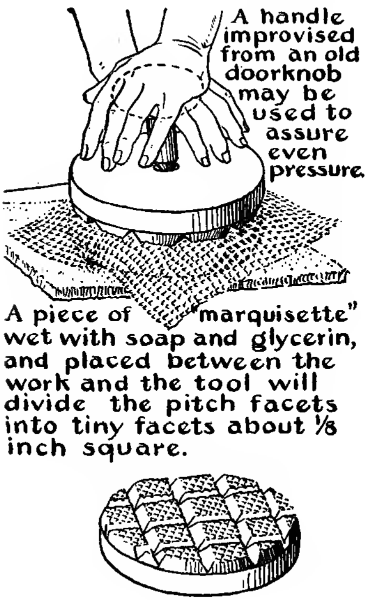

Fig. 19.

Pressing the tool through coarse cloth (such as an onion sack) gives many small facets in addition to the large facets. This results in quick contact of the tool to the glass and smooth action of the figuring tool from the start. (See Fig. 19.)

To avoid astigmatism, the work should be occasionally rotated on the supporting table. In addition, with small tools it is important always to work the tool around the optical surface through an integral number of revolutions.

Hard tools tend to maintain a surface spherical or flat and are useful for generating flats or mirrors which are being worked to a specified radius. On the other hand, soft tools are recommended for working aspheric surfaces. Mirrors made by amateurs may exhibit a better figure than mirrors turned out by professional workers. The reason for this lies in the fact that amateurs usually use soft tools, which produce smooth flowing zones. On the other hand, professional opticians have the skill and knowledge to remove zones quickly with harder tools. In many cases, this rapid working produces faint transition zones, which show up under the most severe testing conditions. It is character-

istic of the commercial optician that he will produce a figure as good as, but no better than, that which his specifications call for.

Manner of figuring various zonal defects, and of making aspheric surfaces of revolution. Focograms and exaggerated profile curves illustrating the manner of figuring various symmetrical defects are shown in Figs. 20, 21, 22, and 23.

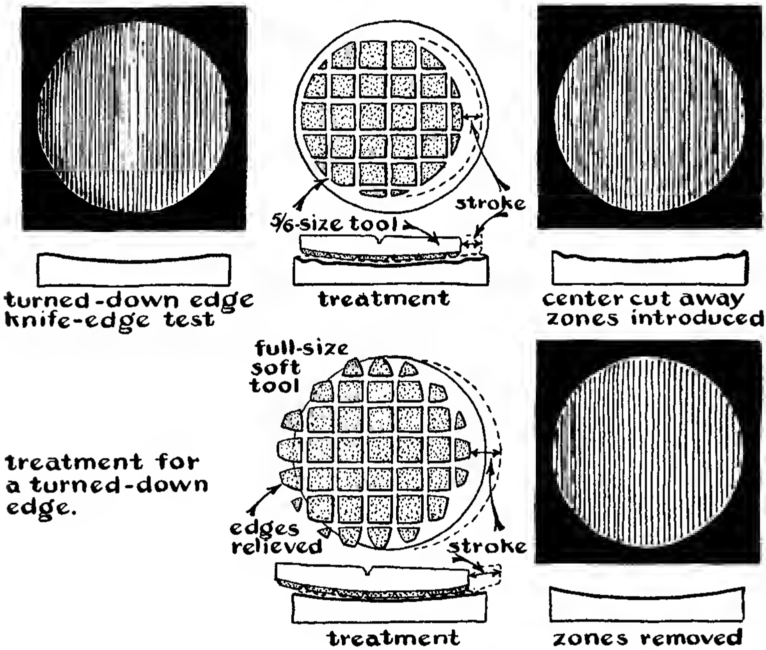

Fig. 20.

The interpretation of focograms is described in a later paragraph. At the upper left of Fig. 20 we see the focogram and exaggerated profile of a mirror with turned-down edge. This is corrected as follows: A $\frac{5}{6}$-size tool and short stroke is used. Two cutting zones are produced. One zone is positioned where the leading edge of the tool comes to the extreme limit of the stroke, and the other is positioned where the trailing edge of the tool comes to the limit of the stroke. Besides making cutting zones, the tool has the further effect

of making the figure more concave. The result is to change the full-line profile curve at the top left of the figure or the dotted profile curve at the top center to the profile exhibiting two sharp transition zones, as shown by the full curve at the top center and right. These transition zones are then smoothed off with a full-size soft tool with relieved edges (to avoid a turned-down edge), using a short stroke.

The treatment with a $\frac{5}{6}$-size tool, as described above, is suitable for removing a turned-down edge from a circular flat; since the final treatment with a soft tool makes the work more convex (see Fig. 17), one can, by the judicious balance of the work done with the two tools, balance the increase in concavity produced by the first by the increase in convexity produced by the second. Fig. 20 shows the procedure applied to a spherical surface.

The sketches at the top of Fig. 21 show how a turned-up edge is turned down with a full-size soft tool.

The second series of sketches of Fig. 21 shows two methods of figuring to remove an intermediary depressed zone. The profile of the full line at the left or the dotted line in the center is changed by the indicated treatment, shown in the center, to the full-line profile in the center or the dotted-line profile at the right. In turn, this is changed by the indicated treatment to the spherical curve represented by the full-line profile at the right. In the first treatment the existing dotted profile, center, is elevated at the center and has a turned-up edge in reference to the imagined curve represented by the full-line profile. This imagined curve is realized with a sub-diameter tool. At the right the full line represents the imagined surface which is realized by removing the narrow sharp transition zones with a full-size soft tool. Inasmuch as this treatment does not change the radius of the work, it is suitable for figuring flats.

By the alternate treatment, which decreases the concavity of the mirror, the cutting zones of the soft full-size tool change the intermediary depressed zone (depressed in reference to an imagined spherical surface) to two sharp

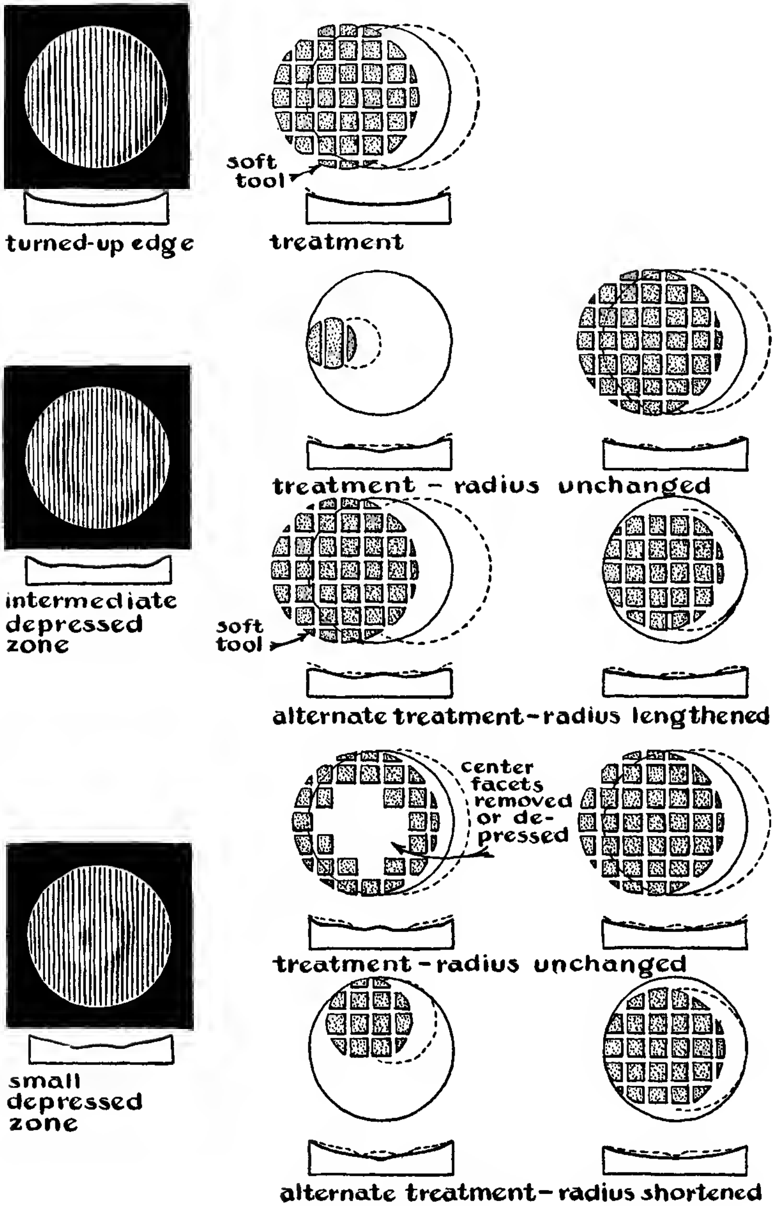
soft
tool
turned-up edge
treatment
treatment - radius unchanged
intermediate
depressed
zone
soft
tool
alternate treatment-radius lengthened
center
facets
removed
or de-
pressed
treatment-radius unchanged
small
depressed
zone
alternate treatment-radius shortened

Fig. 21.

elevated zones on a second imagined spherical surface. These elevated zones are then managed with a sub-diameter soft tool as illustrated.

Two treatments for a small depressed zone near the center of the work are illustrated in the bottom series of Fig. 21.

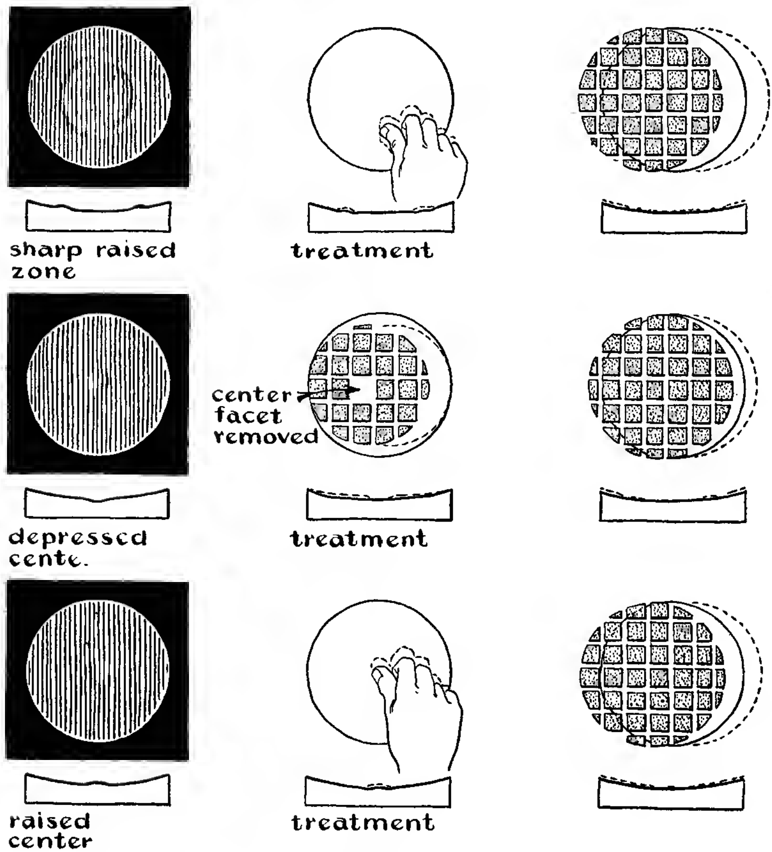

Fig. 22.

By one, the first imagined surface lying wholly under the glass surface requires the removal of an outer layer represented by the difference between the dotted starting profile in the center and the full-line final profile in the center. The next imagined surface, now a spheric one, leaves several

sharp zones to be removed by the usual treatment with a full-size soft tool.

The alternate treatment goes from the primary defective surface to one with an intermediary elevated zone relative to the desired spheric surface. A chordal stroke is used. The elevated zone is removed by a second larger-size tool.

In working on small zones in large mirrors or relatively large zones in small mirrors the optician has as possible figuring tools the thumb, the fingers, and the ball and heel of his hand.

Fig. 22 shows how a narrow elevated zone may be removed with the thumb and how a depression may be removed with tools from which a facet has been removed. The thumb is used with extreme caution, applied lightly for one revolution at first, and then, if necessary, for a few more complete revolutions. There is a danger of overcompensating for the elevated zone with the cutting zone of the thumb, because small polishing tools cut very rapidly.

In testing an optical surface which has been figured by the fingers, one must allow enough time for the heat developed by the friction of the fingers to be dissipated. Even for one revolution, this heating will produce a false zone, by expansion of the glass, which may be higher than the original zone.

The top of Fig. 23 shows how a spheric mirror can be parabolized with a star tool. The focogram at the top right gives the appearance of the parabolic surface when it is tested at the center of curvature. The focogram of a parabolic profile tested at the mean center of curvature exhibits the character of a soft raised intermediary zone.

The second series of Fig. 23 shows an alternate parabolizing procedure and focograms of the appearance of the figure of the mirror, as tested at the focus, before and after the use of the method. The advantage of testing a parabolic mirror at the focus is evident: The optician works toward a uniform distribution of light over the mirror face. The advantage of testing at the focus over testing at the center of

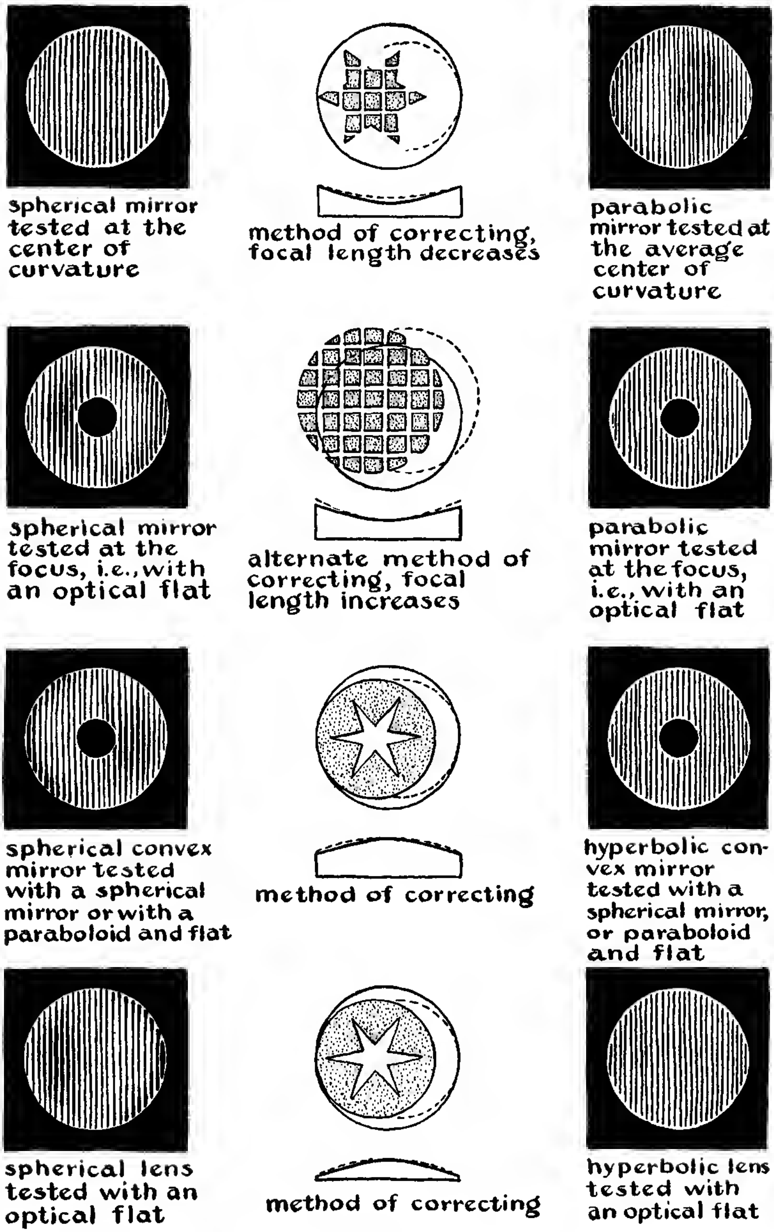
spherical mirror tested at the center of curvature
method of correcting, focal length decreases
parabolic mirror tested at the average center of curvature
spherical mirror tested at the focus, i.e., with an optical flat
alternate method of correcting, focal length increases
parabolic mirror tested at the focus, i.e., with an optical flat
spherical convex mirror tested with a spherical mirror or with a paraboloid and flat
method of correcting
hyperbolic convex mirror tested with a spherical mirror, or paraboloid and flat
spherical lens tested with an optical flat
method of correcting
hyperbolic lens tested with an optical flat

Fig. 23.

curvature is especially great when zones are being removed. Zones which are practically invisible if the mirror is examined at the center of curvature become quite conspicuous when it is tested at the focus.

The last two series of Fig. 23 show procedures that may be used for hyperbolizing.

Astigmatism. The correction of astigmatism is more difficult than the removal of central symmetric zones. Cylindrical defects and, in general, all defects which are not symmetrical about the center of the work produce astigmatism. These defects must be worked out by hand. The rule of procedure is the same as it is for zonal defects—namely, the polishing is done on the high portions of the surface. Transition zones are removed with a full-size tool in the regular manner. The simplicity of this rule must not, however, be allowed to obscure the fact that the correction of astigmatism is one of the most delicate operations required of the optician, and that aside from a knowledge of what is to be done it requires considerable manual dexterity. The tendency of tools to cut fastest near their periphery and especially where their edges come to rest is to be continually kept in mind. The complete removal of astigmatism in an optical surface is the apogee of good workmanship, while its avoidance is the result of experience.

Optical testing. There are many applications for optical tests besides their employment to guide figuring. For example, one may wish to know the figure of a finished spherical concave mirror, a flat, or perhaps a lens of unknown quality. Also, the testing methods described here can be used to test gratings. The Foucault knife-edge test is employed by the Schlieren-methode for photography of sound wave fronts.[6]

Newton's fringes. The simplest optical tests are interference tests using monochromatic light of wave length λ.

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[6] Töpler, A., *Pogg. Ann.*, *131*, 33, 180 (1867).
Wood, R. W., *Physical Optics*, page 93. New York: The Macmillan Company, 1934.

The fringes manifest by a thin air film between optical surfaces are called Newton's fringes. They represent lines of equal optical separation of the surfaces. Between two adjacent fringes the optical thickness of the air film varies by an amount $\lambda/2$, and the fringes may be interpreted as contour lines for the surface of one glass referred to the surface of the other glass, which is usually a flat or spherical test surface.

The fringe system between two flats, if they are slightly inclined to each other and are illuminated with monochromatic light, is a series of parallel equispaced straight lines.

A cylindric surface of long radius of curvature in contact on a line with a flat gives straight fringes of unequal spacing.

A spherical convex or concave on a flat gives concentric circles.

Fig. 24 illustrates a box for testing optical surfaces in contact with a flat and the appearance of the fringes under different conditions.

The appearance of a convex spheric or cylindric surface on a flat is the same as the appearance of a concave surface. The difference in distance between the surfaces at one fringe and at the adjacent fringe is $\lambda/2$; but the sign of the difference, that is, whether the separation is increasing or decreasing, is not known. The following rule may be employed to differentiate between a concave and a convex surface. The exhibited curved fringes expand away from their center of curvature when the head is lowered or moved away from the normal to the flat if the surface is concave, while, if it is convex, they contract toward their center of curvature.

Newton's fringes are particularly suited to making a comparison between a "flat" of unknown quality and a master flat. Also, they may be employed for testing surfaces of a definite radius by pressing them against a master plate of the same radius but opposite curvature. In this case, white light rather than monochromatic light is generally used, and deviations from the master are determined by the residual color of the interference pattern.

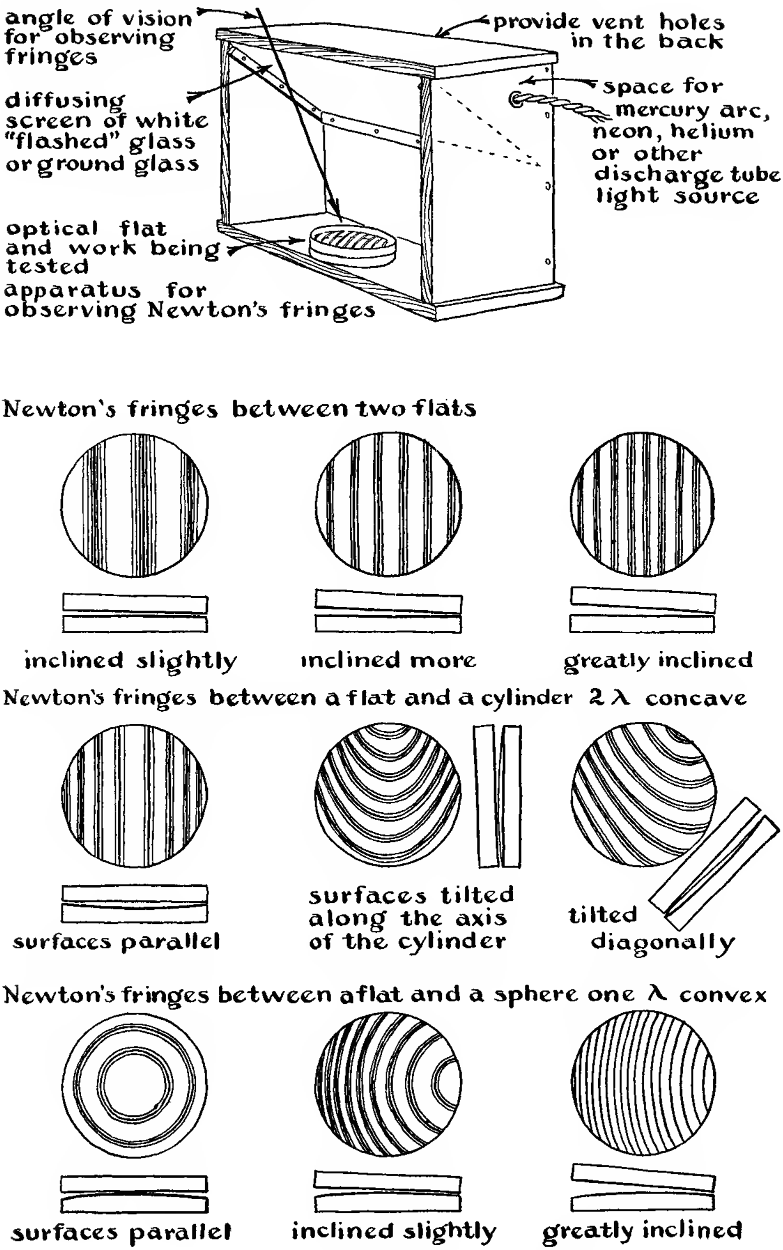
angle of vision for observing fringes
provide vent holes in the back
diffusing screen of white "flashed" glass or ground glass
space for mercury arc, neon, helium or other discharge tube light source
optical flat and work being tested
apparatus for observing Newton's fringes
Newton's fringes between two flats
inclined slightly
inclined more
greatly inclined
Newton's fringes between a flat and a cylinder 2 λ concave
surfaces parallel
surfaces tilted along the axis of the cylinder
tilted diagonally
Newton's fringes between a flat and a sphere one λ convex
surfaces parallel
inclined slightly
greatly inclined

Fig. 24.

When precision tests are made of a "flat" against a master flat and the fringes are observed at other than normal incidence, it is necessary to have the fringes running parallel to the plane of reflection, or they will be curved, even though the work is flat. Deviations of the fringes from a straight line are estimated by comparison with a stretched wire or thread.

Haidinger's fringes. Haidinger's fringes are excellent for testing the quality of plane parallels. Fig. 25 shows how

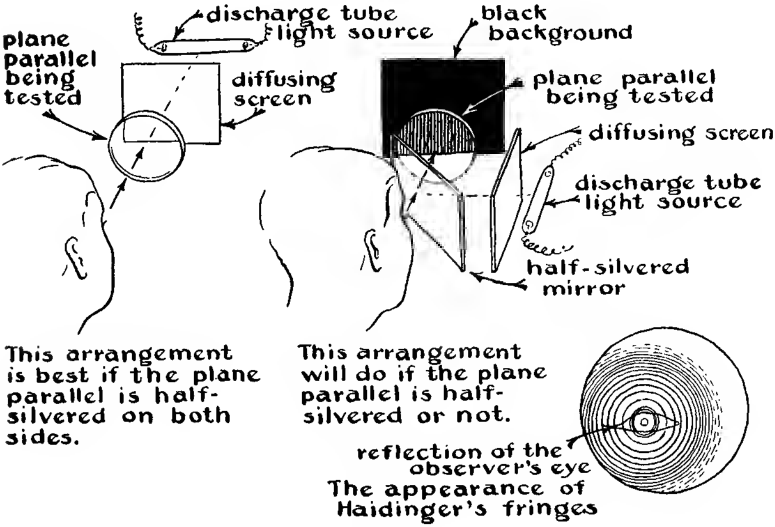

Fig. 25.

Haidinger's fringes are observed. The usual manner of observing Haidinger's fringes is shown at the right in Fig. 25, and the appearance of the fringes and their positioning in respect to the reflected image of the observer's eye are shown in the lower right of this figure. These fringes are arranged like the Newton's fringes produced by a sphere on a plane. They are different in that Newton's fringes are observed by focusing the eye on the thin air film between the plane and sphere, whereas Haidinger's fringes are observed at infinity either with the eye or with a telescope. Newton's fringes

represent the locus of points of equal optical thickness, while Haidinger's fringes represent the locus of points where rays "from the eye" make equal inclination to the plane-parallel plate. The Haidinger fringes are observed at normal incidence, and the plane-parallel plate is moved laterally to apply the test to different areas of the work. A variation of thickness, from one end of a plane parallel to the other, results in the appearance or disappearance of fringes. If the plate gets thicker, fringes appear. The appearance and disappearance of one ring corresponds to $\lambda/2n$ change in thickness. For the most delicate testing, a telescope is used. A large field telescope equipped with a filar micrometer may be used to measure the diameter of the rings. With this telescope the appearance of about one tenth of a ring can be detected. For glass having an index of 1.5, one tenth of a ring represents a difference of thickness of 1.5×10^{-6} cm or approximately 0.5×10^{-6} inch.

Eyepiece tests. Another important means of examining the quality of image-forming systems of mirrors or lenses is to inspect an imaged pinhole light source. A high-power magnifier, such as a 14X Hastings triplet, is suitable for examining the image. This test is called the eyepiece test because it is essentially the test which is applied when one observes a star in the eyepiece of an astronomical telescope on a good night. The eyepiece test is the most sensitive optical test for astigmatism. The infrafocal and extrafocal images should be examined, as well as the focal image. It is advisable to record the results of this test by drawing rough distribution curves representing the light intensity along a horizontal diameter of the image. Fig. 26(a) illustrates eyepiece images for a good (though not perfect) spheric mirror tested at the center of curvature. Fig. 26(b) illustrates the eyepiece test for an overcorrected parabolic mirror tested at the center of curvature, and (c) illustrates the test applied to a mirror with very slight astigmatism.

Fig. 33 illustrates the eyepiece test in comparison with the Foucault, Ronchi, and Hartmann tests.

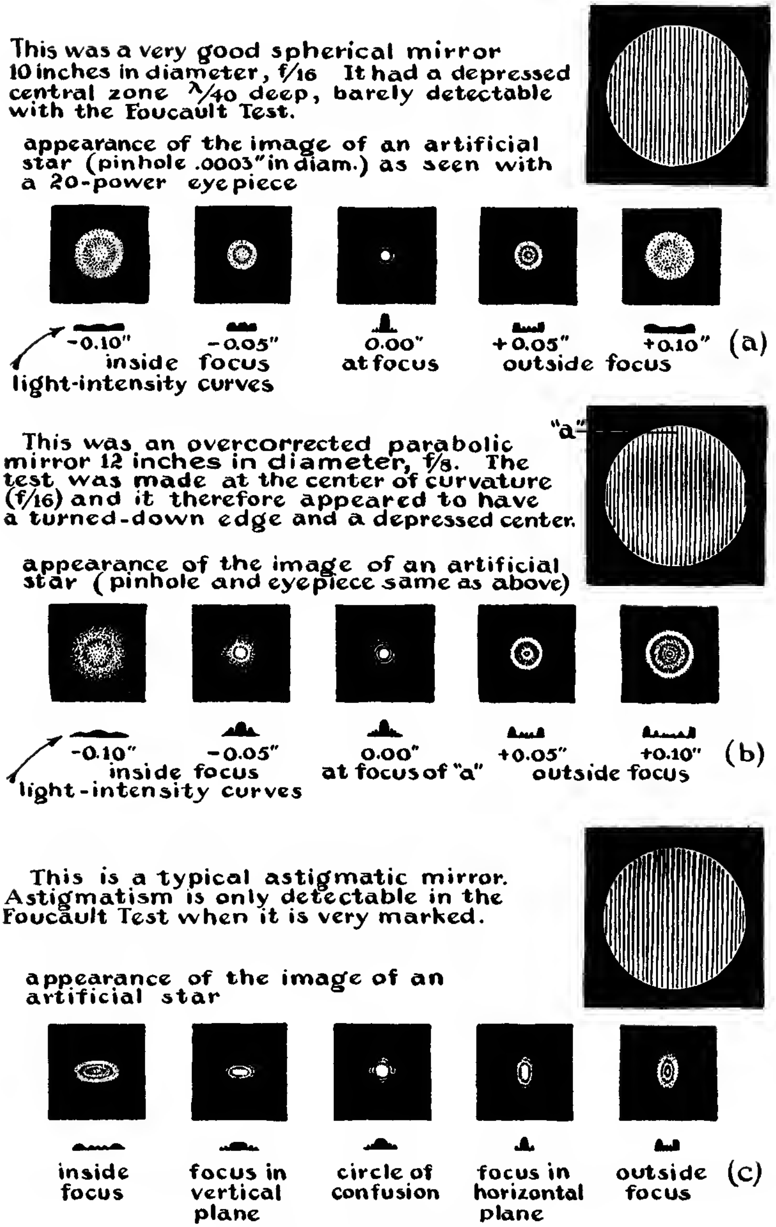

Fig. 26. Eyepiece image test.

Foucault knife-edge test. The Foucault knife-edge test is usually employed for the detection of central spherical aberration, particularly in testing work of fairly large aperture, such as lenses or mirrors used for astronomical telescopes.

The test is simplest as applied to a spherical concave surface of long radius. A small hole is pierced in thin metal

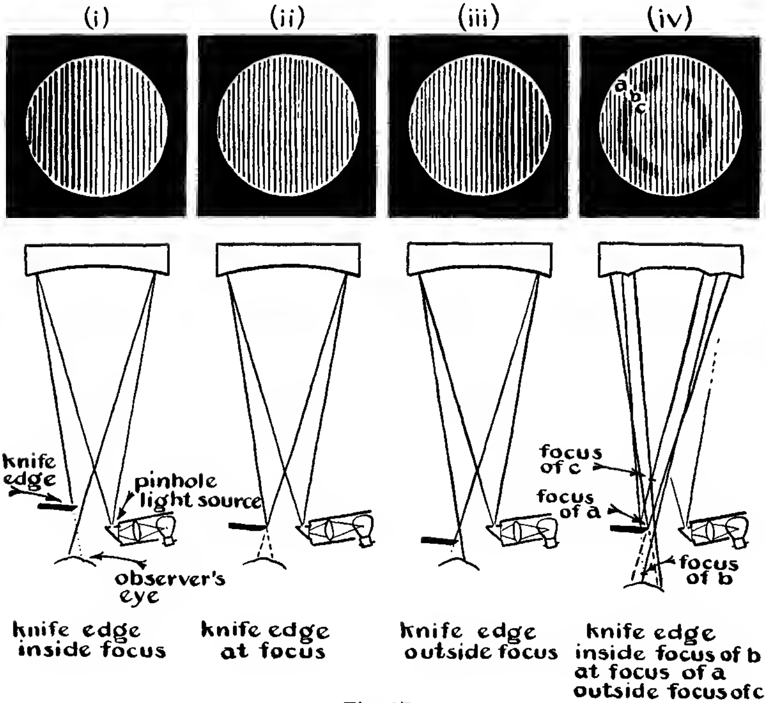

Fig. 27.

sheet with a sharp needle and illuminated by means of a lamp, together with a suitable optical system.[7] This hole is located near the center of curvature of the mirror. (See Fig. 27.) Light from it is reflected by the mirror to form an image at an equal distance on the opposite side of the center

[7] Several layers of the thin metal sheet are laid together on an anvil, and a sharp needle is driven halfway through them. They are then separated and the one with a suitable hole is selected. Each pierced sheet has a small hole of a different size and all the holes are round.

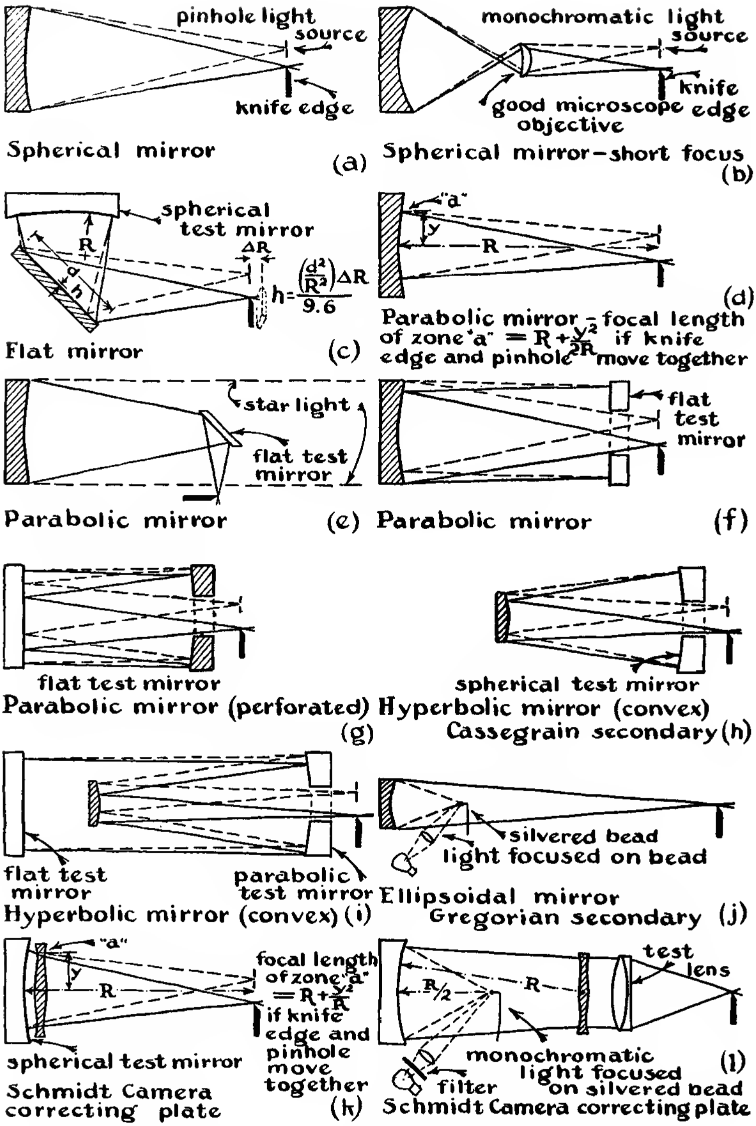

Fig. 28. Arrangements for carrying out the Foucault test:

(a) Testing of a spherical mirror at the center of curvature.
(b) Testing of a short-focus spherical mirror.
(c) Testing a flat with an auxiliary spherical mirror. If knife edge and pinhole move together, a lack of flatness represented by a sagittal distance h introduces astigmatism between the horizontal and vertical focus. The relation between h and ΔR is given.

(d) Zonal testing of a parabolic mirror at the center of curvature. *R* is the radius of curvature at the center.
(e) Testing of a parabolic mirror at the focus with starlight.
(f) Testing of a parabolic mirror at the focus with an auxiliary testing flat.
(g) Alternate procedure for testing a parabolic mirror with a flat.
(h) Testing of an hyperbolic mirror with a spherical testing mirror.
(i) Testing of an hyperbolic mirror with a parabolic mirror and flat.
(j) Testing of an elliptic mirror.
(k) and (l) Testing of a Schmidt lens.

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of curvature. When the eye is placed behind this image so as to receive light from all parts of the mirror, the whole aperture will appear evenly illuminated. Then if an opaque screen, the so-called knife edge, is moved laterally across the focal point, the whole aperture will appear to darken evenly, that is, if the mirror is truly spherical, as in Fig. 27(ii). If the knife edge is moved across the cone of light a short distance inside the focus, its shadow, as it appears on the mirror, moves in the same direction as the knife edge, Fig. 27(i); if it is placed outside the focus, the shadow moves in the opposite direction, Fig. 27(iii). It is possible by this means to locate the focus of the mirror with great precision.

In the case of an imperfect mirror, such as the one shown in Fig. 27(iv), all rays do not converge to a single point, and if the knife edge intercepts the converging light rays as reflected from the mirror, the aperture will appear to be unequally illuminated; some rays are completely cut off by the knife edge, whereas others pass by it and so reach the eye. The mirror shown at the right has an intermediary raised zone. For the inside half of the zone (c) the focal length is shorter than it is for the outside half (b). With the knife edge advanced into the mean focus of the converging rays, those rays from the areas which have their center of curvature exactly at the position of the knife edge are attenuated; rays from (c) reach the eye without attenuation, while rays from (b) are cut off entirely by the knife edge. Accordingly, (c) and (b) appear very bright and dark respectively.

The appearance of the mirror with the knife edge and eye in the positions indicated is as if it were made of plaster and

illuminated at grazing incidence with an imaginary light source.[8] Usually the pinhole source is on the right side of the center of curvature and the eye on the left. In this case, if the knife edge cuts the image from left to right, the observer, thinking of this imaginary light source as illuminating the plaster disk from the right, interprets its shadows in accordance with their apparent inclination. For a lens, the observer interprets the shadows by thinking of the illumination as coming from the left.

Various more complicated setups for making the Foucault test are shown in Figs. 28 and 29. In these two figures a

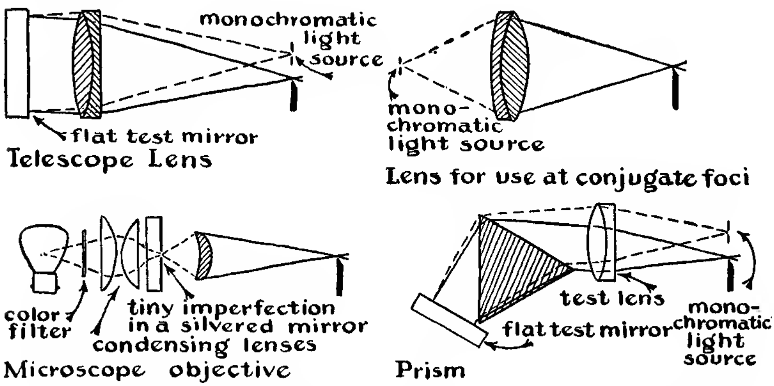


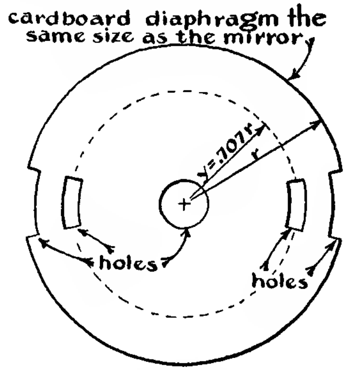
Fig. 29. Foucault tests for achromats to be used to focus parallel light and diverging light. Also, tests for a microscope objective and a prism.

test mirror or lens of unquestioned quality (or at least of known quality) is shown clear, while the tested mirror or lens is cross-hatched.

Zonal knife-edge testing. Aspherical mirrors, such as paraboloidal ones, can be tested at their mean center of curvature without an auxiliary testing flat by measuring the radii of curvature of the glass at various zones. The mirror is covered with a diaphragm of cardboard with holes opposite the zones to be tested. The simplest diaphragm has holes at the center, at the edge, and at 0.707 of the radius, as

[8] See *Amateur Telescope Making, Advanced,* article on Foucault's shadows by E. Gaviola, page 76.

illustrated in Fig. 30. If the mirror is parabolic, the characteristic shadow shown in the upper right of Fig. 23 will appear when the mirror is viewed without the diaphragm. With the diaphragm, the measured difference in focus of the center and the zone at the rim will be $r^2/2R$, where R is the mean radius of curvature of the mirror and r the radius of the mirror. This test is suitable for testing small mirrors to determine when a raised intermediary zone, as illustrated in Fig. 23, is carried sufficiently far, to parabolize the mirror.



Typical zonal diaphragm of a parabolic mirror
For this diaphragm, if the focal length of the center is R, the focal length of the intermediate zone should be $R + r^2/4R$, and the focal length of the rim should be $R + r^2/2R$. Example — for a 6-inch mirror, f = 4 feet, the focus at the center will be 96 inches, at the intermediate zone 96" + 0.023", and at the rim 96" + 0.047." The dimension R (96") need not be precisely measured.

Fig. 30.

Diaphragms for very large parabolic mirrors, or mirrors of focal ratio of $f/4.5$ or greater, are constructed so that the radius of curvature of a large number of zones can be measured. Ordinarily, mirrors of aperture $f/10$ or less need not be parabolized unless their diameter is greater than 24 inches.

Another procedure for quantitative application of the knife-edge setup has been described by E. Gaviola.[9] By this procedure the inclination of different zones is determined relative to a mean surface for the mirror by measuring the position of the knife edge which intersects the light rays reflected from these zones.

In any knife-edge setup, and especially where accurate quantitative zonal measurements are to be made, it is important to avoid parallax. Although a setup like the one

[9] Gaviola, E., *J.O.S.A.*, *26*, 163 (1936).

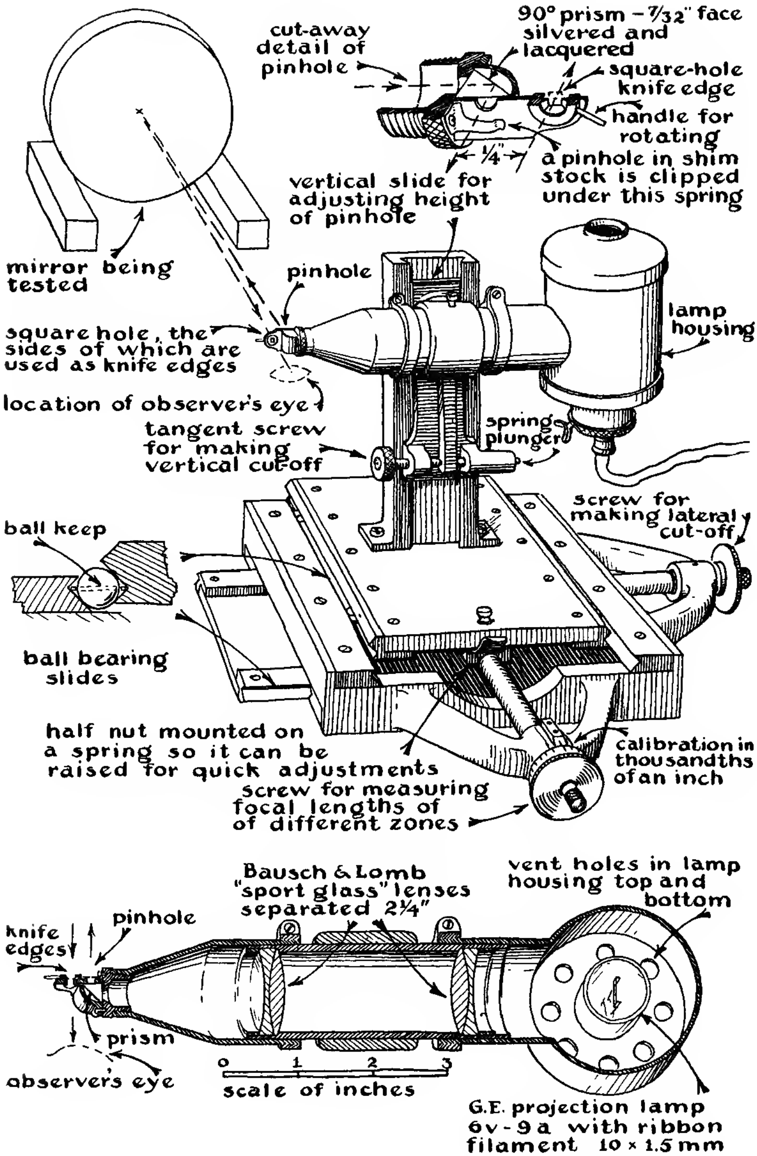

cut-away detail of pinhole
90° prism – 7/32" face silvered and lacquered
square-hole knife edge
handle for rotating
1/4"
a pinhole in shim stock is clipped under this spring
vertical slide for adjusting height of pinhole
mirror being tested
pinhole
square hole, the sides of which are used as knife edges
location of observer's eye
lamp housing
tangent screw for making vertical cut-off
spring plunger
screw for making lateral cut-off
ball keep
ball bearing slides
half nut mounted on a spring so it can be raised for quick adjustments
calibration in thousandths of an inch
screw for measuring focal lengths of of different zones
Bausch & Lomb "sport glass" lenses separated 2 1/4"
vent holes in lamp housing top and bottom
knife edges
pinhole
prism
observer's eye
0 1 2 3
scale of inches
G.E. projection lamp 6v - 9a with ribbon filament 10 × 1.5 mm

Fig. 31.

shown in Fig. 27, using a simple pinhole and knife, is suitable for qualitative tests on small mirrors of long radius, a more elaborate setup is usually required.

Parallax appears whenever a Foucault test is made on more than one mirror, such as a test on a parabolic mirror at its focus with an auxiliary flat. (See Fig. 28.) This parallax is due to the fact that a ray from the pinhole strikes the parabolic mirror at one point and is subsequently reflected, after returning from the flat, at a different point on the parabolic mirror. The displacement between these points on the paraboloid mirror is somewhat less than the displacement between the pinhole and the knife edge. Even so, the displacement may be sufficient to yield results that are quite misleading. As a result of parallax one does not get an indication of the character of the mirror at either of the two indicated points but rather a kind of average for the two points. This information is of little value and may be quite misleading if the effect of errors at one point of the parabolic mirror is compensated by opposite errors at the other.

A knife-edge testing device is illustrated in Fig. 31. Fig. 32 shows two attachments for it which may be used to

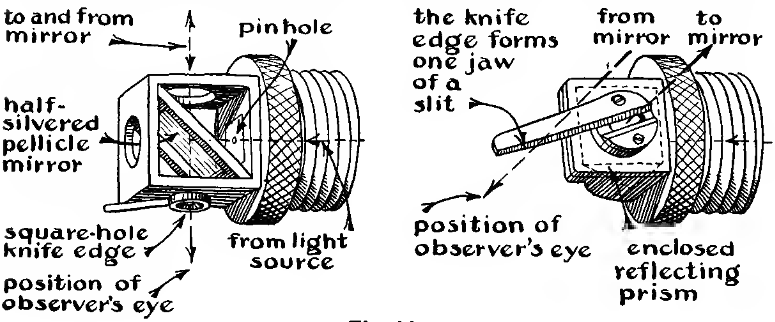


Fig. 32.

avoid parallax. The device at the left eliminates parallax by eliminating the displacement between the knife edge and the pinhole—a virtual image of the pinhole formed by means of a half-silvered pellicle mirror lies exactly on the knife

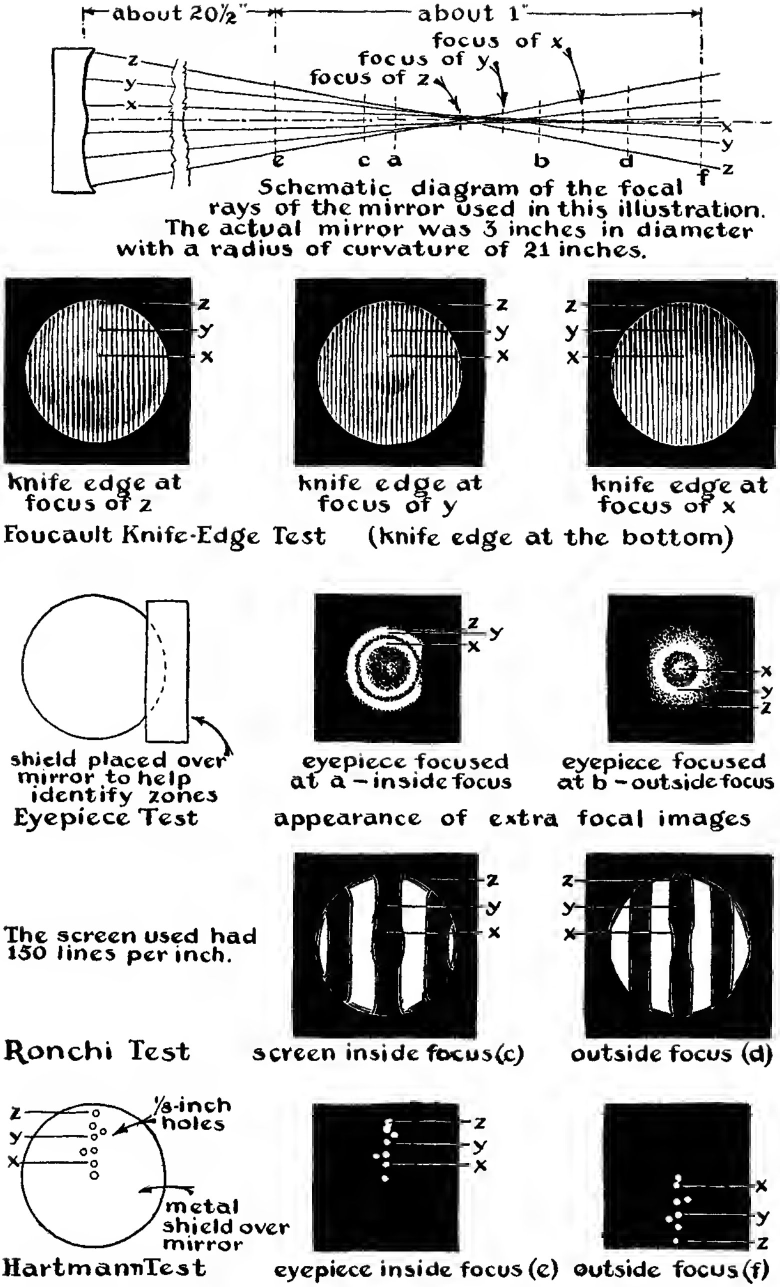


Fig. 33. Comparison of Foucault, eyepiece, Ronchi, and Hartmann tests of a defective mirror.

edge. A pellicle mirror is made by flowing lacquer on an inclined glass plate. After the lacquer is hard, it is stripped off the glass under water. The film of lacquer is then mounted on the flat surface of a brass frame and half-silvered by the evaporation process.

The device at the right uses a slit instead of a pinhole. This device avoids parallax by the simple expedient of removing it by half a revolution in azimuth from the testing diameter.

The Ronchi test. The Ronchi test will be treated here only briefly, since it is not widely employed and its interpretation is not simple.[10] A small light source illuminates the mirror through a ruled surface (about 100 lines per inch), and the image is also formed through another section of the same ruled surface. For comparison, the Foucault test of a defective mirror is shown at the top of Fig. 33. Below, we have the results of the eyepiece test and Ronchi test of the same mirror, and, at the bottom, the Hartmann test is illustrated. Fig. 34 shows a simple quick way of testing a lens with the Ronchi screen. A good lens gives straight Ronchi lines.

Hartmann's test. Hartmann's test is similar to the Ronchi test for a lens, illustrated in Fig. 34. A diaphragm, such as the one shown at the bottom left of Fig. 33, is prepared with several appropriately spaced holes. This diaphragm is placed directly in front of the mirror or lens. The Foucault test determines errors in the mirror by the lateral positioning, relative to their neighbors, of various rays as they pass through the focus; the Hartmann test determines the positions of these rays, relative to their neighbors, at points either inside the focus at (e) or outside of the focus at (f). The relative position of the holes in the plate and the appearance of the rays, as observed with the eyepiece at (e) and (f), are shown in the figure.[11]

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[10] Anderson, J. A., and Porter, R. W., *Astrophys. J.*, *70*, 175 (1929).

[11] For further treatment of optical testing, see articles contained in *Amateur Telescope Making, Advanced*, and references cited therein.

The advantages of the Hartmann test over the others illustrated in Fig. 33 are that it is not necessary to locate the mean focus, and that the results of the test are easily recorded photographically, both of which features make it particularly useful for figuring lenses for the ultraviolet region of the spectrum.

Lining up a system of mirrors. In the more complicated testing setups shown in Figs. 28 and 29 it is often quite

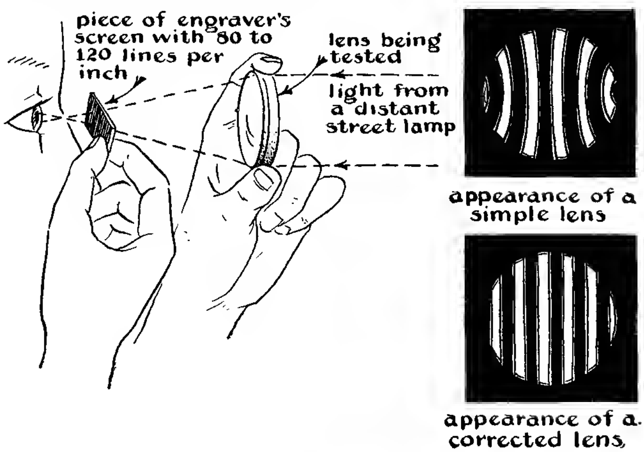

Fig. 34.

difficult to get the mirrors or lenses lined up. The appearance of coma in the eyepiece image, however, can be used to advantage for this. The coma of a system not properly lined up is quite strong and indicates clearly in what direction the mirrors are to be adjusted to get round images.

Some opticians put two white threads at right angles to each other across the face of one of the mirrors. When these threads and all of the secondary images of them viewed from the focus appear symmetrical, the system is in alignment.

Two methods of generating optical surfaces. As we have already pointed out, the optician's task is defined as the generation of accurate surfaces on mirrors, lenses, prisms, and so forth, which possess a high polish. This is ordinarily done by hand or with the modified Draper machine, as

described before. Or it may be done with a high-speed hand-lever machine in the manner described below. The procedure with a modified Draper machine or by hand is slow, but it yields the most accurate results. The modified

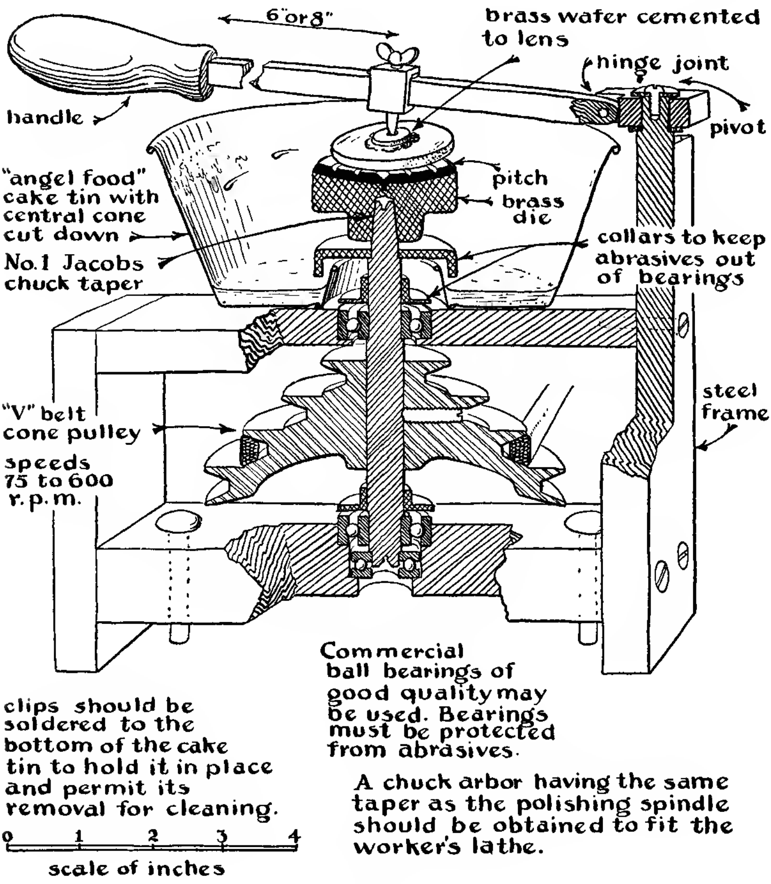

Fig. 35.

Draper machine illustrated in Fig. 10 uses a single crank and allows for counterbalancing of the tool, automatic control of the tool, slow smooth stroking, and easy placement of the work. In contrast with this, the hand-lever machine shown in Fig. 35 features high speed and simplicity. The

spindle is run at about 100 to 600 r.p.m. Naturally, the heat thus generated, as well as the high speeds of cutting, makes work of the highest precision impossible.

Working optical surfaces on the hand-lever machine. The tool used with the hand-lever machine may be attached to a high-speed spindle as shown in Fig. 35, or the work may be attached with wax to the spindle and the tool applied above. In the former case, a socket for the pivot point of

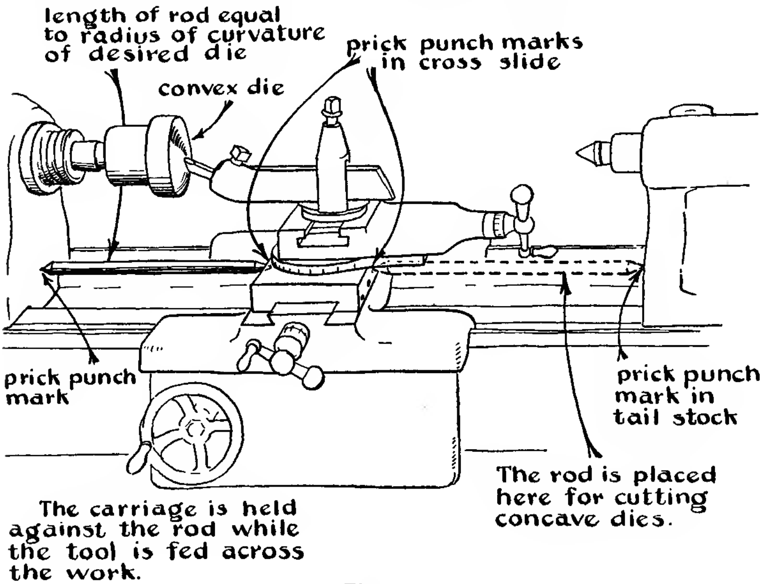

Fig. 36.

the hand lever is waxed to the work with a mixture of 2 parts coal-tar pitch to 1 part sieved wood ashes. When the tool is applied above, the socket is turned in the back of it.

The preliminary grinding may be accomplished on the hand-lever machine with a sub-diameter ring tool of iron, as with the Draper machine. When this ring tool is moved back and forth across the center of the spinning work with a short stroke so that there is no overhang of the tool, the surface is made concave. A long stroke with overhang gives a convex surface. The tool is pivoted and allowed to

spin freely, and 90 Carborundum with water is fed on it to accomplish the grinding. The growth of the curve in the work is measured with templates. These are usually cut on a lathe from a thin sheet of brass or bronze.

The final grinding is done on the hand-lever machine with a spherical brass tool of the same diameter as the work. The spherical tool is made as follows: A brass male and female part are turned on the lathe to the same curvature in the manner illustrated by Fig. 36. These are then lapped together with Carborundum to generate complementary spherical surfaces. If a lathe is not available, they may be separately ground with the hand-lever machine to an approximate fit with a third metal ring tool and then lapped together. It is important to cut a cavity in the center of the one to be used as the grinding tool. The cavity should have a diameter of about one twentieth of the tool diameter.

After the proper curve is approached in the work by grinding with the ring tool, the spherical brass tool is substituted, and the final grinding is carried out with 90, F, and 600 Carborundum and 302½ emery. During the grinding process the offset of the tool in respect to the work should never be so great that the tool and the work rotate in opposite directions.

Polishing is accomplished on the hand-lever machine with rouge on a pitch lap. The brass tool used for grinding may be warmed and coated with a layer of hard pitch or pure beeswax for polishing. While the wax is still warm, it is pressed to the proper shape with the already fine-ground work (wet with soap and glycerin solution) to give a layer of pitch about $\frac{1}{8}$ to $\frac{1}{4}$ inch in thickness. As for grinding, this lap is cut away in the center to form a cavity of one twentieth of the tool diameter. Also, the pitch is cut to form annular grooves. These grooves facilitate contact between the pitch and the work. The pitch lap should be frequently trimmed.

If the central cavity removed is too broad, the tendency is to polish the edges first, while if the central cavity is small and pitch is trimmed off the edges of the tool, it will polish

the center first. Also, whether the polish progresses faster in the center of the work or near the edge depends on the offset. A little offset favors polishing the edges fast, and a big offset makes the progress of polishing greater in the center. One can easily keep track of the progress of the polishing by shining a strong light on the work and observing the "grayness" produced by the residual grinding pits.

It is difficult to balance all these factors, and in practice one should observe how the polish progresses. If the polish is not progressing satisfactorily, the offset can be altered or the tool trimmed accordingly.

Figuring aspheric lenses on the hand-lever machine is accomplished by polishing with sub-diameter tools and star or ring tools.

Small lenses are aligned on the spindle by tilting them while the blocking wax used to cement them in place is still warm. The spindle is turned slowly, and if an object, preferably a small light source, seen reflected in the surfaces does not describe an eccentric circle as the lens rotates, the alignment is complete.

After being centered on a brass tube mounted in the headstock of the lathe, in the same manner as described above, the work is edged with an iron tool and grits. (See Fig. 6.)

Relationship between two optical surfaces. Although we have emphasized the phases of procedure which are important in generating the optical surface, we have not dealt extensively with the orientation of that surface with respect to the general form of the work or with respect to other optical surfaces. These are matters usually managed in an obvious manner. However, in the construction of prisms, especially right-angle prisms and plane parallels, the manner of getting proper relationship between the two flat surfaces involved is not so obvious. A half-hour of polishing on the Draper machine or a few minutes of polishing on the spindle machine will usually put enough polish on ground surfaces to allow their relationship to be tested on a spectrometer table or with other optical tests. Right-

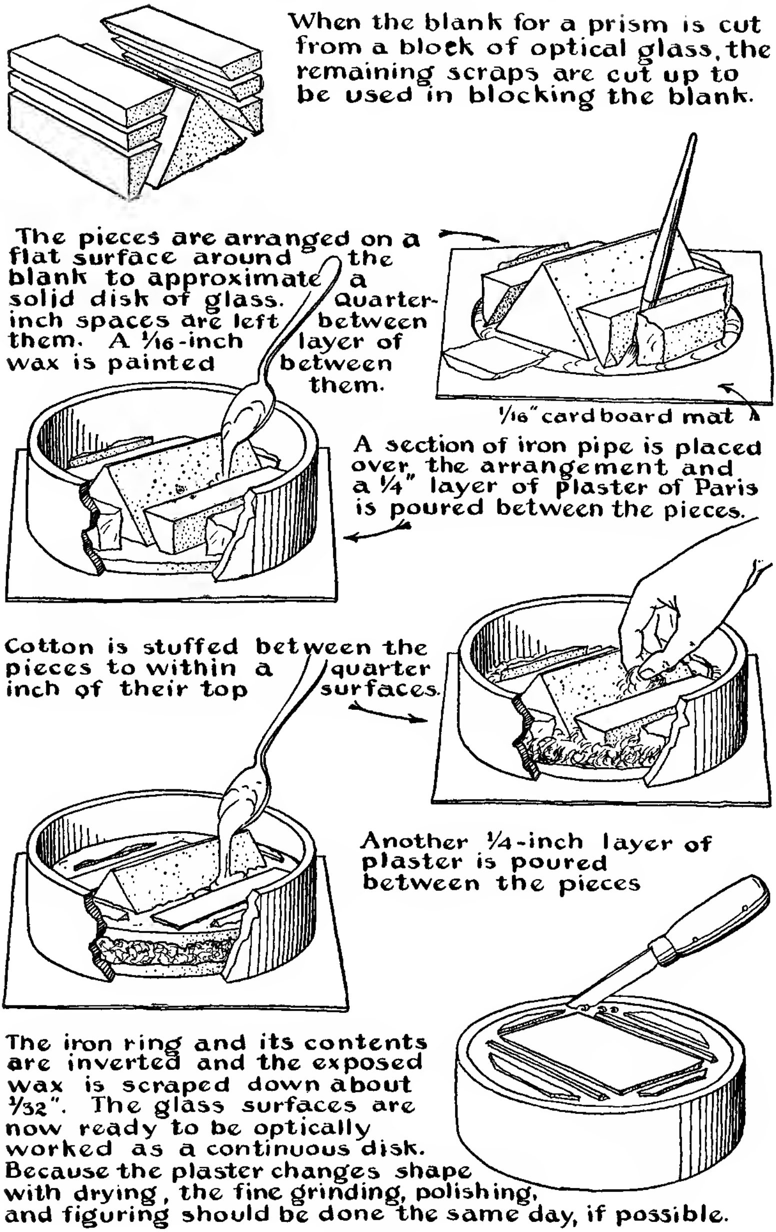
When the blank for a prism is cut from a block of optical glass, the remaining scraps are cut up to be used in blocking the blank.
The pieces are arranged on a flat surface around the blank to approximate a solid disk of glass. Quarter-inch spaces are left between them. A 1/16-inch layer of wax is painted between them.
1/16" cardboard mat
A section of iron pipe is placed over the arrangement and a 1/4" layer of plaster of Paris is poured between the pieces.
Cotton is stuffed between the pieces to within a quarter inch of their top surfaces.
Another 1/4-inch layer of plaster is poured between the pieces
The iron ring and its contents are inverted and the exposed wax is scraped down about 1/32". The glass surfaces are now ready to be optically worked as a continuous disk.
Because the plaster changes shape with drying, the fine grinding, polishing, and figuring should be done the same day, if possible.

Fig. 37.

angle prisms are tested by employing their property of deviating a light beam exactly 180°. This test is sensitive to about 1 minute of angle when it is made with the naked eye, and if it is made using a telescope equipped with a Gauss eyepiece, it is sensitive to about 1 second of angle.

Plane parallels are ground to be flat and parallel to about $\frac{1}{20,000}$ of an inch. Good micrometers are used to test the glass for parallelism to this accuracy. The final optical precision is obtained by figuring. The test using Haidinger's fringes, described before, is used to guide the figuring. Plane parallels are usually made with circular faces to be cut up later into rectangles if necessary.

Blocking. Inasmuch as round glass surfaces are more easily figured than square or rectangular ones, it is advisable to mount a prism blank in a metal ring as shown in Fig. 37, together with auxiliary glasses having the same coefficient of expansion, to make up a circular array of glass surfaces. This circular array is held in the metal ring with plaster of Paris, and the ensemble is then worked as a single disk of glass. The parts may be immersed in a single thick layer of plaster, but it is best to imbed them in a double layer of plaster as shown in Fig. 37. A mixture of 3 parts plaster to 2 parts water is used. This gives an almost nonshrinking, although not very strong, cement. The work may be coated first with a thin layer of beeswax in cases where free lime or moisture in the plaster might attack the glass. After the plaster of Paris sets, its surface is shellacked to make it impervious to water. The grinding and figuring should be finished in one day. Otherwise, owing to "aging" of the plaster, the central and auxiliary surfaces will not maintain satisfactory alignment.

Quartz and calcite. When optical surfaces are generated on crystals, it is frequently required to orient the surfaces precisely with respect to the crystal axes. Fig. 38 illustrates the manner in which the optical axis of quartz is precisely located. The crystal is cut at each end with the mud or diamond saw, the cuts being made roughly perpendicular to

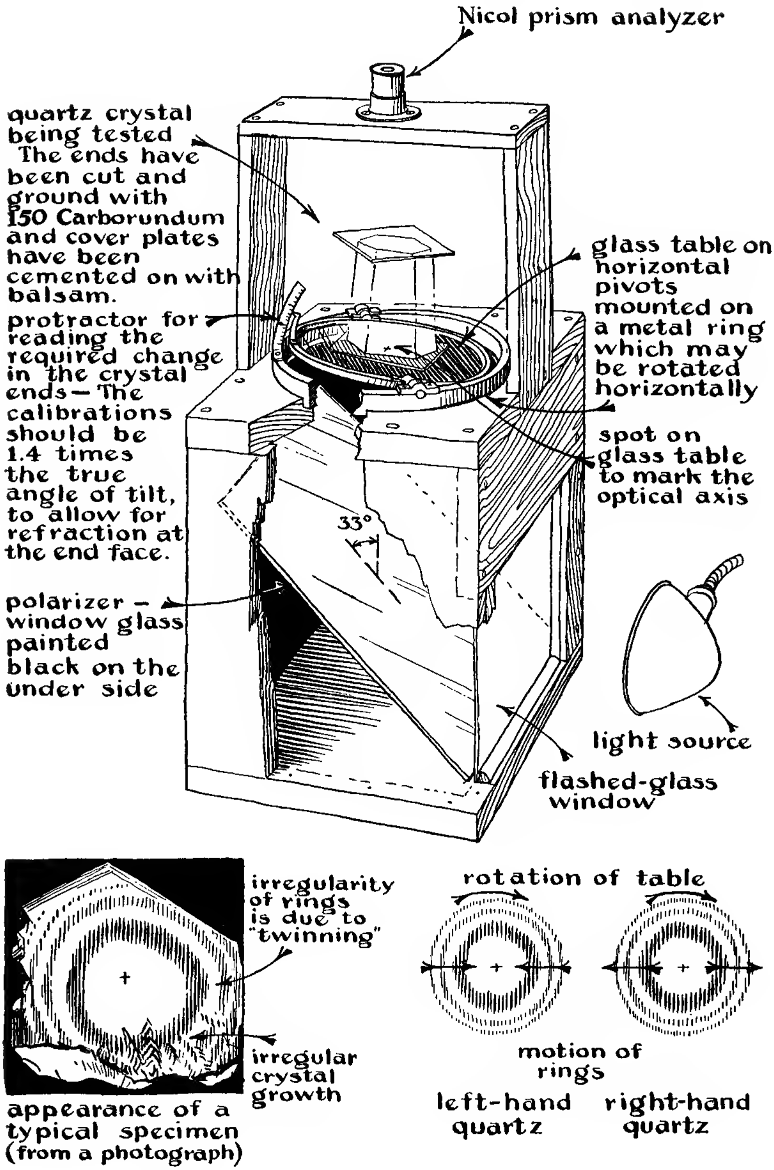
Nicol prism analyzer
quartz crystal being tested The ends have been cut and ground with 150 Carborundum and cover plates have been cemented on with balsam.
protractor for reading the required change in the crystal ends—The calibrations should be 1.4 times the true angle of tilt, to allow for refraction at the end face.
polarizer—window glass painted black on the under side
glass table on horizontal pivots mounted on a metal ring which may be rotated horizontally
spot on glass table to mark the optical axis
33°
light source
flashed-glass window
irregularity of rings is due to "twinning"
irregular crystal growth
appearance of a typical specimen (from a photograph)
rotation of table
motion of rings
left-hand quartz
right-hand quartz

Fig. 38.

the optical axis. These parallel saw cuts are then ground with the abrasives to grade 150 Carborundum and "artificially polished" by cementing cover glasses to the ground

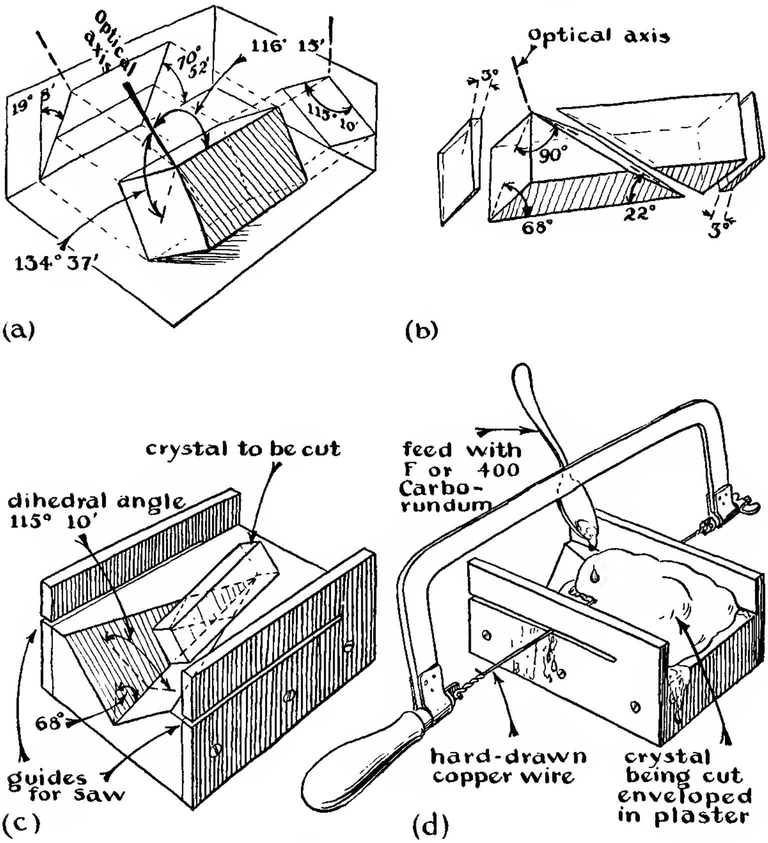

Fig. 39. Calcite:

(a) Orientation of axis.
(b) Cuts for making Nicols.
(c) and (d) Procedure for cutting calcite to make Nicols.

ends with balsam. Polarized light is used to determine the optical axis in the manner illustrated in the figure. The system of rings noted through the analyzer will remain stationary when the crystal is rotated about a vertical axis if the cuts are perpendicular to the optical axis. If the

rings "wobble" as the crystal is rotated, the axis of rotation is to be tilted by means of the gimbals provided (or with wedges) until the fringes are stationary during rotation. The ends are then recut, taking account of refraction (see note on the figure), and the plate retested to check the result.

When properly cut quartz crystal is rotated in a clockwise direction, the rings close in toward the center if the crystal is left-handed quartz and move out if it is right-handed quartz.

An irregular piece of quartz can be roughly examined for striae by immersion in a tank filled with a solution composed of 80 per cent ethyl cinnamate and 20 per cent xylol (by volume). Iron oxide surface stains may be removed from the crystal by washing in oxalic acid solution.

The orientation of the principal axis of calcite is shown at the top of Fig. 39. To cut calcite for making Nicols, the crystal is oriented and mounted in a wooden form having the cutting plane defined by a preliminary saw cut. The cut through the crystal is made by hand by sawing through both plaster and crystal with a hard-drawn copper wire mounted in a scroll-saw frame and charged with Carborundum.

Optical working of crystals. Quartz is the optician's favorite medium. Both the fused and the crystal material are ground and polished by the same procedure as glass.

Calcite crystals, especially large ones, are expensive, and in addition they are soft and easily fractured. Accordingly calcite is always worked by hand with very light pressures. All but the smaller Carborundum grains tend to produce fractures in calcite, and therefore the series F-400-600 Carborundum and 302½ and 303½ emery is recommended for working it. If prisms with very thin edges are to be made, 400 Carborundum is used as the coarsest grit. A beeswax-coated pitch lap is satisfactory for polishing and figuring calcite. For figuring, calcite should be blocked with calcite of the same crystal orientation.

Rock salt is polished and figured on a hard-pitch tool pressed with a glass pressing lap.[12] The desired figure is

[12] Brashear, John A., *Proc. of Am. Assn. for Adv. of Science*, *38*, 166 (1885).

obtained with an overcorrected pressing lap, as the figure obtained on this material is usually convex with respect to that established in the tool by the pressing lap. For example, in making flats, one would use a slightly concave pressing lap ($\frac{1}{1000}$ of an inch in a 4-inch disk or 60-foot radius of curvature). Rouge in saturated salt solution is used to start the polishing. Fig. 40 shows the arrangement of the pitch tool which is placed below the work, and a chamois skin used for drying the work. The work is rubbed against the lap until the rouge is almost dry. It is then

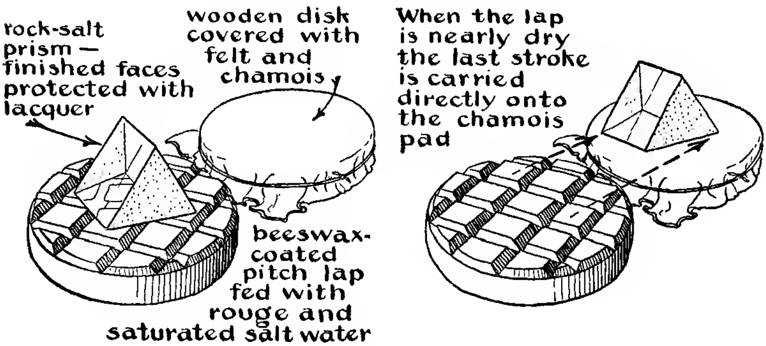

Fig. 40.

kept moist with the breath for the final strokes and is slipped off the tool onto the chamois to be dried. This technique should be practiced on test pieces before big work is undertaken. The first face of a prism or lens is lacquered or waxed to prevent attacks by moisture while the second face is being worked. The pitch tool is coated with beeswax. Beeswax is useful for even softer materials than rock salt, such as potassium chloride, potassium bromide, and even potassium iodide.

Polishing of metals. Perhaps the most important metal in optics is speculum metal. It is very hard, exhibits a conchoidal fracture like glass, and is worked by the same procedure, being ground with the same sequence of grits. The polishing tool should have narrow facets. It is often

advantageous to do the final figuring of speculum surfaces with the metal face turned down to avoid scratching.

Stellite is also worked like glass except that longer grinding periods (two to three times that for glass) are required. Ordinarily pitch polishing tools are used with rouge or chromium oxide as polishing agent. One should try to "hold" the figure from the grinding stages until polishing is completed.

Hard steel is worked in the same manner as glass.

In grinding soft steel, a still softer metal, such as copper or lead, is used as a grinding tool.

Soft steel and hard-drawn copper are difficult to polish, but they can often be managed with a polishing tool coated with a mixture of paraffin and oxide of tin. As much oxide is added to the molten paraffin as it will take without crumbling. This mixture is applied hot with a swab to the pitch polishing lap.

If a metal tends to etch or discolor during polishing, it is advisable to try carbon as a polishing agent (charcoal ground in a ball mill and washed). Chromium oxide will often give a bright polish in cases where rouge would discolor the metal.

The very soft metals—silver, soft copper, gold, and so forth—cannot be easily surfaced by the ordinary optical methods. They become charged with the grits and refuse to grind. Silver circles are brightened by rubbing moistened cigarette ashes with the thumb back and forth in a direction parallel to the engraved lines.

The Schmidt camera. The Schmidt camera is an image-forming device which combines features not possessed by any lens system, and, while it has some disadvantages, it may well prove to be a natural solution to many more instrumental problems than those to which it has already been applied.[13]

The camera has had considerable application in astronomy, particularly meteor photography and survey work of

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[13] Strömgren, B., "Das Schmidtsche Spiegelteleskop," *Vierteljahrschrift der Astronomischen Gesellschaft*, *70*, 65 (1935).
Smiley, C. H., "The Schmidt Camera," *Popular Astronomy*, *44*, 415 (1936).

large star fields. It has been applied to stellar spectrographs, and it is believed that it will have other applications in research where extreme speed, a long spectral range, and a large field are important. Two awkward features of the Schmidt camera are its curved focal plane and the inaccessibility of the plate or film holder. The curvature of the focal surface is $R/2$, where R is the radius of curvature of the primary mirror. The focal surface is convex toward the sphere.

The construction of a Schmidt camera is so difficult that it should not be undertaken except by one with considerable optical experience. The following is intended primarily as a description of it.

The scheme of the instrument is shown at the top of Fig. 41. It consists of a spherical primary mirror and a Schmidt lens, which corrects the primary mirror for spherical aberration. The lens is located at the center of curvature of the spherical mirror, and its deviation from flatness is so small that no great error of achromatism is produced by the dispersion of the index of refraction of the glass from which it is made. However, as an optical figuring job this deviation is great enough to make the construction of the lens difficult. This is because the curve deviates as much from any sphere as it does from flatness, so that all the construction difficulties of making aspheric surfaces are encountered.

The Schmidt lens may have several contours, as illustrated in Fig. 41. The variation of thickness may be obtained by putting the curves entirely on one side of the plate or on both sides. The variation in the thickness Δt of a plate of diameter $2r$, expressed as a function of the distance from the center of the plate y and the radius of curvature R of the primary spherical mirror, can be represented by any one of the family of curves

$$\Delta t = \frac{y^4 - ky^2r^2}{4(n-1)R^3},$$

where k may have any value between 0 and 4.

The characteristics of some of the curves are as follows: Where $k = 4$, the lens is too thick; where $k = 0$, the slope

at the edge is so steep that the construction difficulties are great; where $k = 1.5$, the achromatism is best; where $k = 1$, the slopes are moderate, the color characteristics

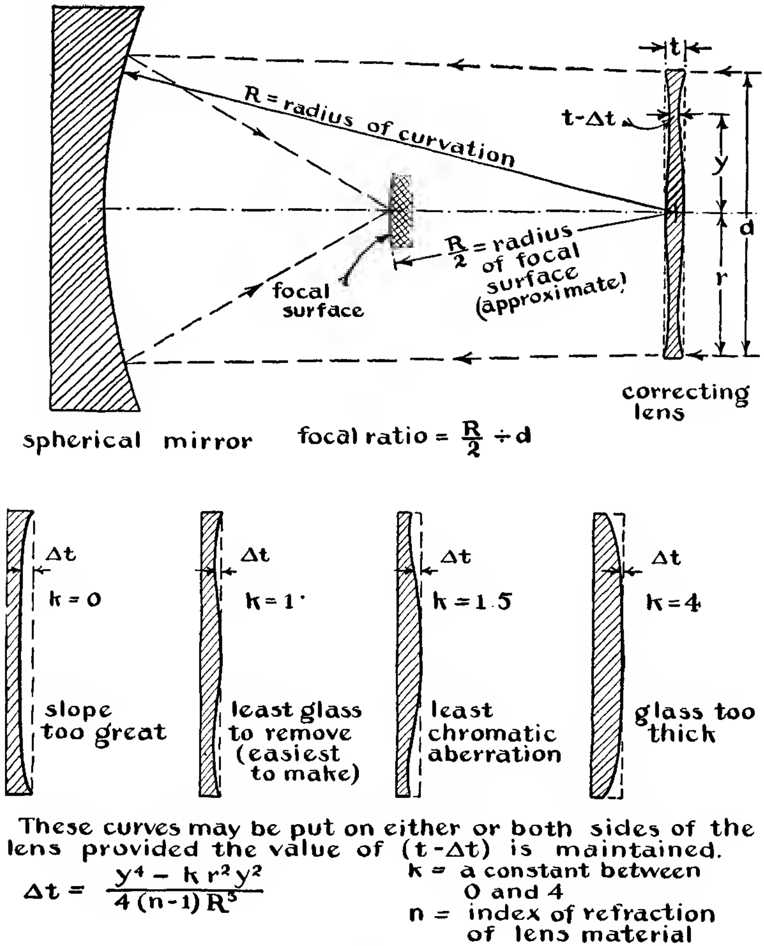

Fig. 41.

are good, and the curve can be put half on one side of the plate and half on the other. In the case where $k = 1$, the curve requires the least glass to be removed.

The Schmidt lens is made of Uviol glass or even fused quartz if the camera is to be used for photography in the

ultraviolet spectrum. The Schmidt camera has been made to numerical apertures as fast as $f/0.6$. Such a camera is much faster than a camera using a lens of corresponding aperture because there are fewer glass surfaces to penetrate, and the light losses are correspondingly less.

The Schmidt plate is ground and polished with a special ring tool. Each of the glass facets for grinding or pitch facets for polishing is mounted on a separate spring as in

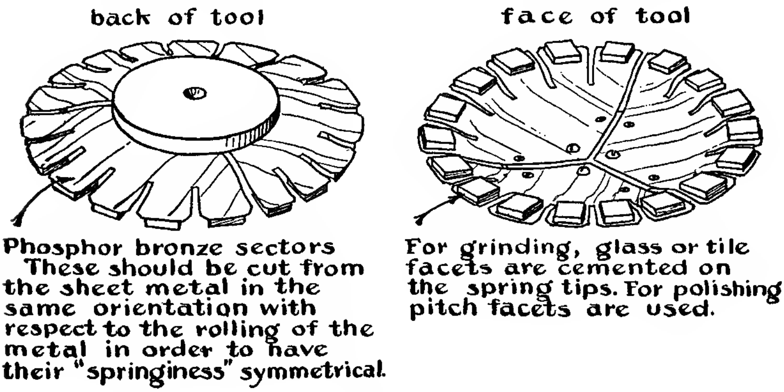

Fig. 42.

Fig. 42. This or a similar flexible construction of a tool is used since considerable deformability is required of it.

The curve $k = 1$ requires the thickness at the center to be the same as that at the edge. This is indicated when a straightedge laid across the work will touch the center but not rock on it. The minimum thickness of the plate at $y = 0.707\,r$ is determined from the thickness at the edge, and the value of Δt calculated from the equation. The intermediary zone is depressed by grinding until this minimum thickness corresponds with that required as measured by a micrometer.

Figuring may be guided by several testing schemes shown at the bottom of Fig. 28.

CHAPTER III

Technique of High Vacuum[1]

SOME of the equations from the kinetic theory are important in the design, construction, and operation of vacuum apparatus. Accordingly, we will begin our treatment of the technique of high vacuum with a discussion of them. The derivations of these equations are omitted, since we are interested only in their applications.

The laws of ideal gases. The laws of ideal gases are represented, mathematically, by Eqs. 1 and 2.

$$P_1 = \frac{w_1}{M_1} R \frac{T}{V}. \tag{1}$$

$$P_T = P_1 + P_2 + \ldots P_n. \tag{2}$$

P_1 represents the total pressure exerted on the walls of a vessel containing w_1 grams of a gas of molecular weight M_1, when this vessel has a volume V and is maintained at an absolute temperature T. If more than one gas is present, for example, if the vessel contains w_1 grams of one gas of molecular weight M_1, w_2 grams of a second gas of molecular

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[1] This chapter is intended primarily to supplement the works on vacuum technique listed below:

Dunyoer, L., *Vacuum Practice.* New York: D. Van Nostrand and Company, 1926.

Dushman, S., *Frank. Inst., J.*, *211*, 689 (1931).

Dushman, S., *High Vacuum.* Schenectady: General Electric Company, 1922.

Goetz, A., *Physik und Technik des Hochvakuums.* Aktges. Braunschweig: Friedrich Vieweg und Sohn, 1926.

Kaye, G. W. C., *High Vacua.* New York: Longmans, Green and Company, 1927.

Newman, F. H., *The Production and Measurement of Low Pressures.* New York: D. Van Nostrand and Company, 1925.

weight M_2, and so forth, the partial pressure exerted by each gas is given by Eq. 1.

The total pressure, given by Eq. 2, is the sum of these partial pressures. The value of the constant R, the so-called universal gas constant, is independent of the molecular weight of the gas, but its value does depend on the units in which the pressure and volume are expressed. In vacuum work the pressure is usually expressed in millimeters of mercury[2] and the volume in cubic centimeters, in which case R has the value of 62,370.

Eqs. 1 and 2 are based on the assumptions, first, that the molecules are infinitely small and, second, that no intermolecular forces exist. Neither assumption is valid for real gases. Nevertheless, the equations describe the behavior of real gases, especially hydrogen and helium, with sufficient accuracy for our purposes here. Although the equations break down at elevated pressures (pressures greater than 1 atmosphere), they become increasingly precise if the pressure is reduced. And, at pressures encountered in vacuum work, Eqs. 1 and 2 not only apply to the description of the behavior of gases but describe the behavior of many unsaturated vapors as well.

The mean free path. The mean free path is the average distance traversed by molecules between successive intermolecular collisions. The magnitude of this quantity is determined by the size of the molecules and is given by the formula

$$\lambda = \frac{1}{\sqrt{2}\pi n\sigma^2}. \tag{3}$$

σ represents the molecular diameters and n the number of molecules per cubic centimeter. Values of the mean free

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[2] P is usually expressed by physicists in millimeters of mercury pressure. Other units are the following:

$$1 \text{ bar} = 0.75 \times 10^{-3} \text{ mm}$$
$$1 \text{ Tor} = 1 \text{ mm}$$
$$1 \text{ micron} = 10^{-3} \text{ mm}$$

path for nitrogen calculated by Eq. 3, using 3.1×10^{-8} cm for the molecular diameters, are given in Table I.

TABLE I

MEAN FREE PATH OF NITROGEN AT 0° C.

Pressure in Millimeters of Mercury	Mean Free Path
760	8.5×10^{-6} cm
1	0.0065 cm
10^{-3}	6.5 cm
10^{-4}	65 cm
10^{-5}	6.5 m
10^{-6}	65 m
10^{-9}	65,000 m

Viscosity and heat conductivity. The viscosity and heat conductivity of a gas, like the mean free path, depend on the molecular diameters. As a result, we have the relationship between the mean free path and the viscosity η,

$$\eta = \tfrac{1}{3}\rho v_{\text{av.}}\lambda, \tag{4}$$

and the relationship between the viscosity and the thermal conductivity K,

$$K = \eta c_v \epsilon. \tag{5}$$

In these equations ρ is the gas density in grams per cubic centimeter; c_v is the heat capacity at constant volume of unit mass of the gas; and ϵ is a constant, being 2.5 for monatomic and 1.9 for diatomic gases. $v_{\text{av.}}$ is the average velocity of the molecules and is defined by the equation

$$v_{\text{av.}} = \sqrt{\frac{2.1 \times 10^8 T}{M}} \text{ cm/sec.} \tag{6}$$

The relationship between σ, λ, η, and K for various gases is illustrated in Table II.

TABLE II

PROPERTIES OF GASES

Gas	Molecular Diameters ($\sigma \times 10^8$ cm)	Coefficient of Viscosity ($\eta \times 10^6$ cm)	Thermal Conductivity ($K \times 10^6$ cm)
Hydrogen	2.47	86	318
Nitrogen	3.50	166	52
Oxygen	3.39	187	56
Helium	2.18	189	339
Argon	3.36	210	38.9

Kaye, G. W C., and Laby, T. H., *Tables of Physical and Chemical Constants and Some Mathematical Functions.* New York: Longmans, Green and Company, 1936.

Substituting PM/RT for ρ and Eq. 3 for λ in Eq. 4, we see that the pressure cancels. In other words, Eq. 4 predicts that the viscosity will be the same at reduced pressure as it is at ordinary pressures. The experimental verification of this prediction by Meyer and Maxwell was a triumph for the kinetic theory.[3] They measured the damping of a torsion pendulum in a bell jar at pressures varying from 1 atmosphere to about 10 mm of mercury. The damping produced by the viscosity of the air was found to be the same at all pressures.

Eq. 5 predicts that the heat conductivity is also independent of the pressure. This was established experimentally by Stefan.[4]

Eqs. 4 and 5 are derived from the assumption that the mean free path is small in comparison with the size of the apparatus. Table I shows the pressures at which this assumption becomes invalid.

If Meyer and Maxwell had reduced the pressure in their bell jar below about 10^{-1} mm, they would have observed a decrease in the damping effect on the torsion pendulum.

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[3] Meyer, O., and Maxwell, James Clerk, *Pogg. Ann.*, *125*, 40, 546 (1865), *143*, 14 (1871).

[4] Stefan, J., *Akad. Wiss., Ber.*, *65*, 2, 45 (1872).

Likewise, if Stefan had extended his observations, he would have found a decrease in the heat conductivity towards 10^{-1} mm and its complete disappearance below about 10^{-4} mm.

Pumping speeds. Consider that a vessel contains a gas at pressure P and opens through an aperture to a region where a high vacuum is maintained. Further assume that this high vacuum is to be maintained at a pressure so much lower than P that it is essentially a perfect vacuum. The volume of gas escaping through the aperture per unit time, dV/dt, measured at pressure P, is given by the formula

$$\frac{dV}{dt} = A\sqrt{1.32 \times 10^7\frac{T}{M}}\ \text{cm}^3/\text{sec.}, \tag{7}$$

where A is the area of the aperture. The value of dV/dt for air ($M = 29$) at room temperature ($T = 300°$ Kelvin) is 11,700 cc/sec. cm², or 11.7 liters/sec. cm². It is a noteworthy feature of this formula that dV/dt is independent of the pressure in the vessel.

A hypothetical aperture of unit area communicating with an essentially perfect vacuum may be regarded as a pump with a speed of 11.7 liters/sec. Oil and mercury diffusion pumps have two characteristics in common with such an aperture. They have pumping speeds of the same order of magnitude as the aperture, and their observed pumping speeds are roughly constant over a considerable pressure range.

The speed of a diffusion pump is, accordingly, expressed as the volume of gas passing through the throat of the pump measured at the pressure which obtains at the throat. The speed factor of a pump is the ratio of its speed per unit area of the throat to the value 11.7 liters/sec. A good oil diffusion pump has a speed factor of about 0.5 or 0.6. The speed factor for mercury diffusion pumps[5] varies from 0.1 to 0.3.

[5] Ho, T. L., *Rev. Sci. Instruments*, *3*, 133 (1932).

The pumping speed of diffusion pumps can be measured by means of a leak like the one shown in Fig. 1. Gas at atmospheric pressure is allowed to leak into the pumping line. The rate at which the gas is introduced is measured by the motion of a mercury pellet in the calibrated capillary tube. At the same time the pressure at the throat of the pump is determined with a vacuum manometer. The rate dV/dt at which gas passes through the pump is obtained by multiplying the volume which the mercury pellet sweeps through per unit time by the ratio of the pressure in the capillary (that is, the barometric pressure) to the pressure which obtains at the pump throat.

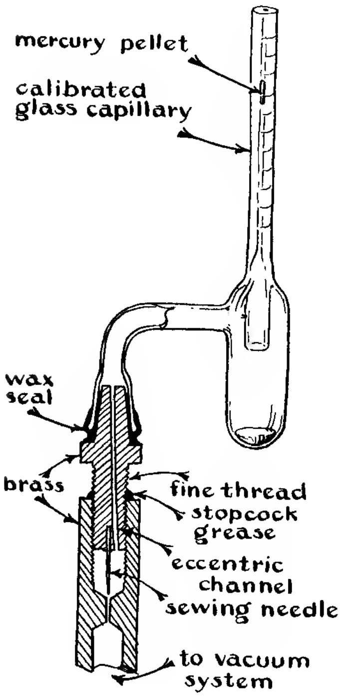

Fig. 1.

Conductance of vacuum pumping lines. Ordinarily, a pump is connected to an apparatus by a tube or system of tubes which constitute the vacuum pumping line. The measured speed of the pump, which we will designate S_0, at one end of the vacuum line is greater than the effective pumping speed, S, at the other end of the line. Naturally, the difference between S_0 and S is small if the pumping tubes are short and have a large diameter. The difference between S^{-1} and S_0^{-1} determines the capacity of a vacuum line. The capacity is the reciprocal of W, the resistance of the vacuum line to the flow of gas. The relationship of the quantities S_0, S, and W is given by the formula

$$\frac{1}{S} = \frac{1}{S_0} + \frac{1}{W}. \tag{8}$$

W, in turn, is defined in terms of tube dimensions by Knudsen's formula,

$$W = 1.59 \times 10^{-5}\sqrt{\frac{273M}{T}}\left(\frac{l}{d^3} + \frac{4}{3d^2}\right)\frac{\text{sec.}}{\text{cm}^3}, \tag{9}$$

where l is the length of the pumping line and d is its diameter, both expressed in centimeters.[6] The first term in the parentheses represents the resistances of the line, while the second term represents the resistance of the two ends of the line (or the resistance of a sharp bend in the line). The second term is usually insignificant in comparison with the first and may be neglected. For example, W. Klose found that a straight pumping channel with four right-angle bends, one with four **T**-shaped enlargements, and a curved tube of equal diameter all exhibited essentially the same pumping speed.[7]

The coefficient of Eq. 9 becomes unity if 29, the molecular weight of air, is substituted for M, room temperature of 300° K. is substituted for T, and $8r^3$ is substituted for d^3, where r is the radius of the tube. It is further required that l' and r be expressed in millimeters and that W be expressed in sec./liter instead of sec./cm³. After making these substitutions and neglecting the second term in the parentheses, Eq. 9 reduces to

$$W' = \frac{l'}{r^3}\frac{\text{sec.}}{\text{liter}}. \tag{10}$$

An an example of the application of Eq. 10, consider a pumping tube of 250 mm length and 5 mm radius. This gives a value of W' equal to 2 sec./liter. Substituting this value in Eq. 8, we see that the pumping speed S can never exceed $\frac{1}{2}$ liter/sec., even if a very fast pump is used, for which $1/S_0$ is practically zero.

Evacuation. The factors determining the rate at which an apparatus is evacuated are the volume of the apparatus, V,

[6] Knudsen, M., *Ann. d. Physik*, *28*, 75, 999 (1908). This formula applies when d is less than the mean free path.

[7] Klose, W., *Phys. Zeits.*, *31*, 503 (1930).

the effective speed of the system of pumps, S, and the limiting pressure which the pumps are capable of attaining, P_0. The method of evaluating the first factor, V, is obvious. The value of S may be calculated from the values of S_0 and W by Eqs. 8 and 10, or it may be measured by connecting the leak and gauge to the apparatus.

The value of P_0 is not easy to estimate, so it is necessary to measure it with a gauge. P_0 does not depend on the pumping speed of the pumps on tight systems which are outgassed. When the system is leaking or giving off gas, P_0 depends on the rate of leaking as well as the speed of the pumps. On a tight outgassed system the limiting pressure for mercury diffusion pumps equipped with a liquid air trap is 10^{-7} mm or less. For oil diffusion pumps without traps the limiting pressure varies from 10^{-5} to 10^{-6} mm, although lower values are occasionally reported. The vacuum attainable with mechanical pumps is usually 10^{-2} to 10^{-4} mm. The water aspirator is restricted to work at pressures above the vapor pressure of water, about 25 mm of mercury at room temperature.

The effect of outgassing on P_0 is illustrated by an experiment described by Dushman.[8] He found a limiting pressure of 0.033 bar for a Gaede rotary pump connected to a vacuum gauge when the connecting glass tube was giving off gas. When the glass tubing, however, was baked out until its surface was free of absorbed moisture and other gases, the limiting pressure was reduced to 0.0007 bar.

The rate at which the pressure is reduced in an apparatus, as determined by the pumping speed S, the volume V, and the limiting pressure P_0, is given by the equation

$$\frac{dP}{dt} = -\frac{S}{V}(P - P_0). \tag{11}$$

The integration of this equation yields

$$(t_2 - t_1) = \frac{V}{S}\log_e\left(\frac{P_1 - P_0}{P_2 - P_0}\right). \tag{12}$$

[8] Dushman, S., *Phys. Rev.*, *5*, 225 (1915).

Eq. 12 is useful, for example, in predicting the time $(t_2 - t_1)$ required for a vacuum system to recover from a surge of gas which raises the pressure to the value P_1. In this case P_2 represents the working pressure required in the apparatus.

If P_2 and P_1 are much larger than P_0, then P_0 may be neglected, and Eq. 12 can be simplified to the form

$$\frac{P_2}{P_1} = e^{-\frac{S}{V}(t_2 - t_1)}. \tag{13}$$

Roughing pumps. The so-called roughing pumps are used to support diffusion pumps because the latter will

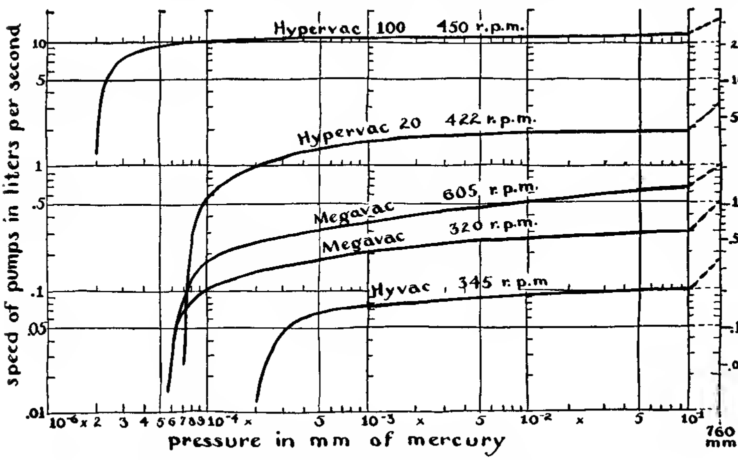

Fig. 2. Pumping speeds of mechanical pumps (data supplied by the Central Scientific Company, Chicago, Illinois).

operate efficiently only against a small differential of pressure at pressures less than a few tenths of a millimeter of mercury. Rotary mechanical pumps are ordinarily used.[9] The pumping speeds of several rotary pumps at various pressures are given in Fig. 2. Other types of pumps, such as the water

[9] The series High-vac, Mega-vac, and Hyper-vac is supplied by the Central Scientific Company, Chicago, Illinois. The Leybold vacuum pumps are handled in this country by James G. Biddle Company, Philadelphia, Pennsylvania. Extremely fast mechanical pumps are manufactured by the Kinney Manufacturing Company, 3541 Washington Street, Boston, Massachusetts.

aspirator, the Gaede rotary pump, and the Sprengel and Toepler pumps, are seldom used now. These pumps are adequately described in the literature.[10]

Outgassing of glass and metals. Outgassing removes gases adsorbed to the surface of glass and metal. It is necessary to outgas exposed glass and metal in order to obtain the highest degree of vacuum. Prolonged heating of glass at 150° to 200°C. in vacuum removes most of the gases adsorbed on the surface, while further heating to 300°C. removes the final monomolecular film of water and adsorbed gases. Gases liberated when the heating is carried above this temperature originate from the decomposition of the glass.[11]

In practice, lead-glass apparatus is outgassed by heating it in an oven or with a soft flame to a maximum temperature of 360°C. for a time varying from 10 minutes to an hour or more. Lime glass and hard glass are heated to 400° and 500°C. respectively. Higher temperatures are to be avoided, since the annealing or softening point of soft glass is only 425°C. and of hard glass 550°C.

Before a glass apparatus is sealed off from the pumps, the seal-off constriction is heated for a minute or two at a temperature just below the softening point of the glass.

When metals are strongly heated in a vacuum, they give off adsorbed gases as well as absorbed gases and gas arising from the decomposition of oxides near the surface. Gases under the surface layer of the metal, both dissolved gases and those held in chemical combination, are difficult to remove, even at elevated temperatures, unless the metal is fused. The metal oxides, with the exception of chromium oxide, are readily dissociated in vacuum at elevated temperatures. Metals which have been fused in vacuum are now available commercially.[12]

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[10] See footnote 1, page 93.

[11] R. G. Sherwood's report on decomposition of glass: *Am. Chem. Soc., J.*, *40*, 1645 (1918); *Phys. Rev.*, *12*, 448 (1918).

[12] These metals may be obtained from the Eisler Corporation, Newark, New Jersey.

Surface gas on tungsten wire is liberated by a temperature of 1500°C. From 70 to 80 per cent of this gas is carbon monoxide, and the remainder is hydrogen and carbon dioxide.[13] The volume of surface gas evolved, measured at standard conditions, amounts to three or four times the volume of the tungsten wire. Sweetser studied the gas liberated by copper, nickel, Monel, and copper-coated nickel-iron alloy (Dumet). He found that these metals rarely gave off a volume of gas greater than the volume of the wire.[14]

Marshall and Norton have studied the gases given off by tungsten, molybdenum, and graphite.[15] After these materials have been outgassed by prolonged heating in vacuum at temperatures above 1800°C., they may be exposed to atmospheric pressure, and the gases which they then take up are readily removed by subsequent reheating to a moderate temperature in vacuum. However, they should not be touched with the fingers.

Many metals may be heated in hydrogen to remove surface contamination. At the same time dissolved gases near the surface of the metal are, in part, replaced by the hydrogen. This substitution is desirable, since hydrogen comes off readily when the metal is subsequently heated in vacuum either in a bake-out oven or by high-frequency induction.

Vapor pressure of waxes. Table III gives the results of Zabel's measurements of the relative vapor pressures of waxes used in vacuum work. The numbers given there represent the results of measurements taken with an ionization gauge.

The wax compounded from shellac and butyl phthalate (see Chapter XIII) should exhibit a low vapor pressure, judging from Table III.

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[13] Langmuir, I., *Amer. Inst. Elect. Engin., Proc.*, *32*, 1921 (1913).

[14] S. P. Sweetser's results are reviewed in Dushman's *High Vacuum*, page 163.

[15] Norton, F. J., and Marshall, A. L., *Reprint No. 613*, General Electric Company (1932).

TABLE III

Vapor Pressure of Material Relative to That of Brass

Material	Ratio
Pyrex	0.7
Iron	3.5
Iron coated with rust	250
Picein	4
Beeswax and rosin	5.5
Glyptal*	8.5
DeKhotinsky (soft to hard)†	15 to 25
Glyptal lacquer (baked)	2
Butyl phthalate	5.4
Stopcock grease	7
Ramsay Fett	85

Zabel, R. M., *Rev. Sci. Instruments*, *4*, 233 (1933).

* Sager, T. P., and Kennedy, R. G., Jr., *Physics*, *1*, 352 (1931).
† Old formula. A new wax is now supplied by Central Scientific Company for which these values may not apply.

Getters. Ordinarily, in the laboratory, a diffusion pump is used to remove the residual gases which roughing pumps cannot remove, and the resulting high vacuum is maintained by continued pumping. There are, however, other methods of removing the residual gases in an apparatus which is sealed off at the pressure attainable with a roughing pump.[16] These methods involve the use of so-called getters, which not only remove the residual gases initially, but maintain the vacuum against the deteriorating effects of subsequent outgassing.

Getters may be grouped into three classes, depending on the manner in which they remove residual gases. Some depend on the physical adsorption of the residual gases on the refrigerated surface of a porous substance like charcoal or silica gel; others absorb the gas in the manner that hydrogen is absorbed by palladium black or tantalum; and still others combine with the residual gas chemically.

[16] Andrews, M. R., and Bacon, J. S., "Systematic Investigation of the Action of Getters in Sealed Tubes," *Am. Chem. Soc., J.*, *53*, 1674 (1931).

The high absorbing capacity of charcoal and silica gel is due in part to their large surfaces. The surface of charcoal, for example, is estimated to be as great as 2500 square meters per gram. Absorbent charcoal to be used for removing residual gas is itself first outgassed by heating it in the vacuum produced by the roughing pumps. It should not be heated above the softening temperature of Pyrex, because it will lose some of its absorption capacity owing to "crystallization" of the charcoal and attendant loss of surface area. After this outgassing the pumps are turned off to isolate the vacuum system, and the charcoal is cooled (preferably with liquid air) to develop its absorbing capacity. The absorbing power of charcoal for various gases at 0°C. and −185°C. (liquid air temperature) is given in Table IV.

TABLE IV

ABSORPTION CAPACITY OF COCONUT CHARCOAL: VOLUME OF GAS AT STANDARD CONDITIONS OF TEMPERATURE AND PRESSURE ABSORBED BY UNIT VOLUME OF CHARCOAL

Gas	0°C.	− 185°C.
Helium	2	15
Hydrogen	4	135
Argon	12	175
Nitrogen	15	155
Oxygen	18	230
Carbon dioxide	21	190

Dewar, Sir James, *Encyclopædia Britannica, 16*, 751 (1911).

Of the metal getters, tantalum is of special interest. It absorbs hydrogen in large volumes—it may absorb as much as 740 times its own volume of gas at temperatures around 600°C. This absorbed gas is given off when the metal is heated in vacuum at temperatures greater than 800°C. At high temperatures, tantalum is one of the metals most easily outgassed. At elevated temperatures the residual gases, oxygen and nitrogen, are also removed by chemical combina-

tion with tantalum. Because of these properties, it is frequently used for radio-tube anodes. The metals columbium and zirconium behave in much the same way as tantalum.

Tungsten and molybdenum, at temperatures above 1000°C., are effective getters.[17] Oxygen is removed by these metals by the formation of oxides which are volatile at temperatures above 1000°C. Hydrogen is dissociated by the high temperature and condenses as atomic hydrogen on the container walls, especially if they are cooled with liquid air.

The alkali metals react with nitrogen, oxygen, hydrogen, and mercury vapor. The absorption of nitrogen, oxygen, and hydrogen is especially strong when the alkali metal is the cathode of a glow discharge.

Barium, calcium, and magnesium are extensively used as getters, since they combine chemically with all residual gases (noble gases excepted). Barium is more active chemically than calcium. These metals are introduced by various ways into the vacuum tubes in which they are to serve as getters. Calcium may be introduced in the form of fresh filings. Barium may be introduced in the form of copper- or nickel-covered wire. Either metal may be formed directly in vacuum by reducing it at elevated temperatures from one of its compounds. Usually the introduced metal is vaporized and condensed on the walls of the sealed-off vacuum system, where it forms a mirror. The getter action of the metal is greater in the vapor phase, although the condensed mirror film, especially a film of barium, will react chemically with residual gases which may subsequently appear in the apparatus.

A metal film exhibits, in addition to the chemical action, a physical action which may be of considerable significance. This physical action, the adsorption of gases, is strong because the metal surface is clean. Dushman gives an elementary calculation illustrating this action.[18] A spherical

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[17] Langmuir, I., *Am. Chem. Soc., J.*, *37*, 1139 (1915); *Indust. and Engin. Chem.*, *1*, 348 (1915).

[18] Dushman, S., *Frank. Inst., J.*, *211*, 737 (1931).

bulb 5 cm in radius containing residual gas at a pressure of about $\frac{1}{10}$ mm of mercury will be completely evacuated when sufficient gas is adsorbed on the inside surface of the bulb or on a clean metal film to form a monomolecular layer.

Water and many vapors may be effectively removed by a trap cooled in liquid air. The density of water vapor in a gas, after it is passed through a liquid air trap, is 10^{-23} mg/liter. The relative effectiveness of some of the more commonly used drying agents is shown in Table V.[19] Of

TABLE V

DRYING AGENTS

Drying Agent	Mg of Water per Liter of Gas Dried at 25°C.
Trap at liquid air temperature	1.6×10^{-23}
P_2O_5	$< 2 \times 10^{-5}$
$Mg(ClO_4)_2$	$< 5 \times 10^{-4}$
$Mg(ClO_4)_2 \cdot 3H_2O$	$< 2 \times 10^{-3}$
H_2SO_4	3×10^{-3}
95 per cent H_2SO_4	3×10^{-1}
$CaCl_2$ (gran.)	1.4 to 2.5×10^{-1}

National Research Council, *International Critical Tables*, Vol. III, page 385. New York: McGraw-Hill Book Company, 1928.

these, phosphorus pentoxide is the one most frequently used in vacuum work. It should be fused to reduce its vapor pressure and to prevent it from flying about when the system is evacuated.

Static and kinetic vacuum systems. Most of the vacuum systems used in physical research fall into two general classes. In the first class we have those systems which are required to be thoroughly outgassed and entirely free from leaks in order to obtain a high degree of vacuum. We will call systems of this type static vacuum systems, in contrast to

[19] A drying agent which has the advantage of being solid when it is saturated as well as when it is "dry" is magnesium perchlorate. This chemical is manufactured by the Arthur H. Thomas Company, Philadelphia, Pennsylvania.

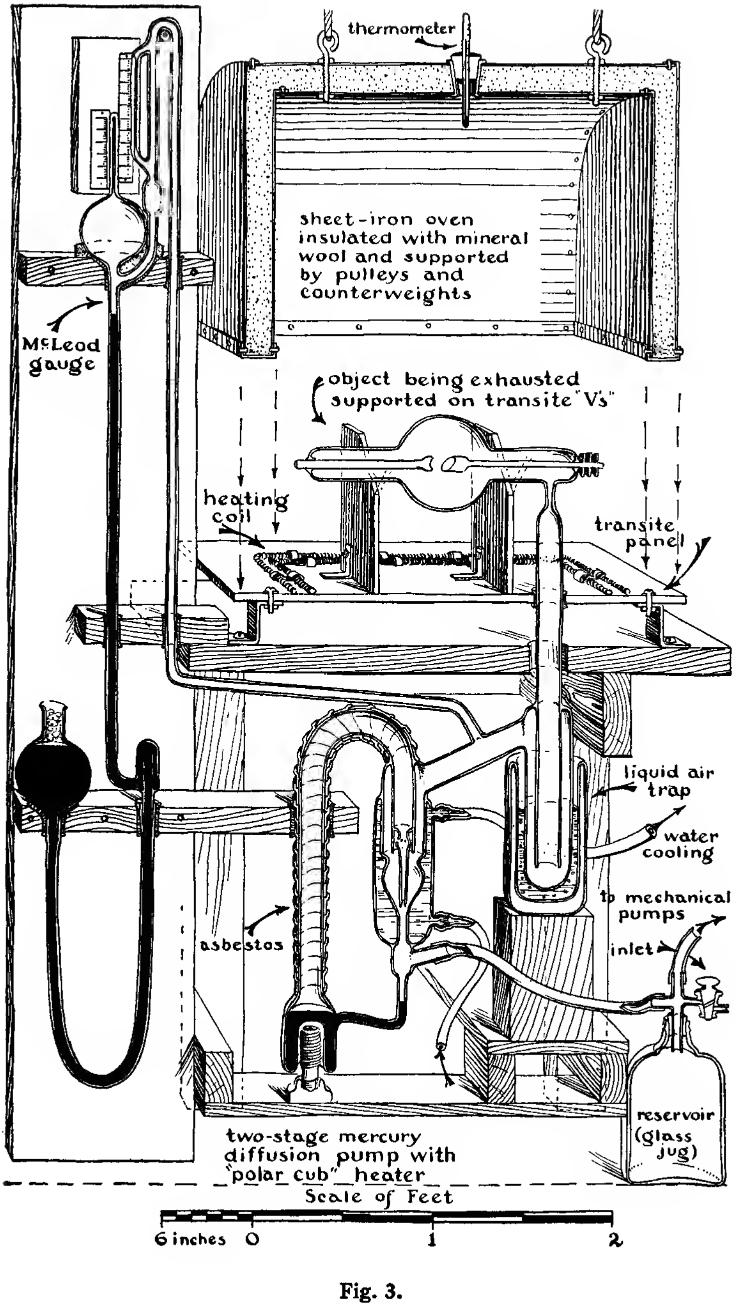

thermometer
sheet-iron oven insulated with mineral wool and supported by pulleys and counterweights
McLeod gauge
object being exhausted supported on transite "V's"
heating coil
transite panel
liquid air trap
water cooling
to mechanical pumps
inlet
asbestos
reservoir (glass jug)
two-stage mercury diffusion pump with "polar cub" heater
Scale of Feet
6 inches
0
1
2

Fig. 3.

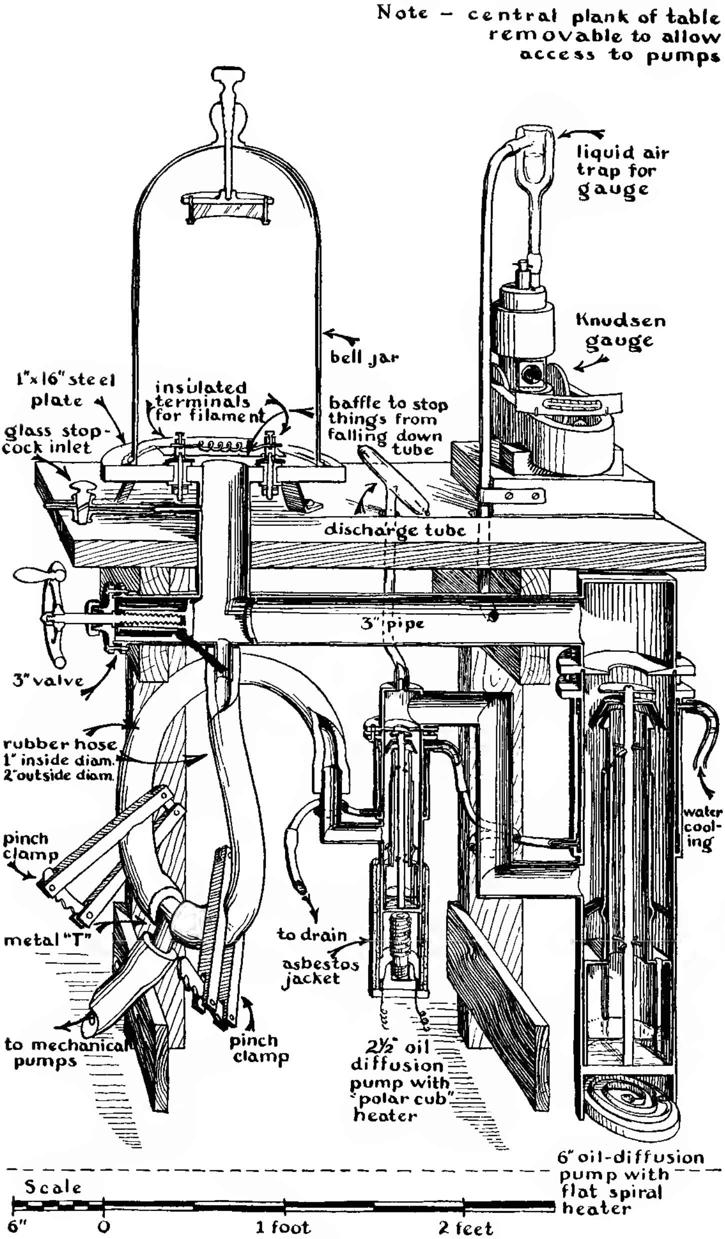
systems in which outgassing from glass on metal parts or in which even small leaks may be tolerated, owing to the use of extremely fast pumps. We will designate systems of the latter type as kinetic vacuum systems.

Fig. 3 illustrates a typical static vacuum system. It represents an X-ray tube being evacuated with a mercury diffusion pump of moderate speed. Pressures as low as 10^{-9} mm (or even 10^{-10} mm) are obtained in some static vacuum systems. Such extremely high vacuum is required for investigating the photoelectric effect, thermionic emission, and other physical phenomena for which the slightest contamination of a surface is to be avoided. Static vacuum systems are not treated extensively here. The reader who is especially interested in them is referred to the literature.

Kinetic vacuum systems are characterized by a limiting pressure of 10^{-5} to 10^{-6} mm obtained by the use of extremely fast pumps. These pumps, as well as the apparatus which they exhaust, are usually made in the machine shop from ordinary brass and steel. The metal is not outgassed as in static vacuum systems.

Kinetic vacuum systems are inferior to static systems, where surface contamination must be scrupulously avoided. They are, however, satisfactory for applications where the function of the vacuum is to allow the unhindered motion of molecular rays, electrons, ions, and light quanta. For example, kinetic vacuum systems have been applied with success to the vacuum evaporation process for metalizing large telescope mirrors, to the maintenance of vacuum in high-voltage X-ray tubes, metal rectifier tubes, and oscillator tubes, and to the evacuation of spectrographs.

Fig. 4 shows a kinetic vacuum system for the metalization of glass mirrors. There are two obstacles in the way of getting a high vacuum in such a system. First, outgassing by heating is precluded on account of the use of wax seals and on account of the fact that the system may contain thick glass mirrors which cannot be safely heated. Second, there is more chance of small leaks appearing than in a



Note – central plank of table removable to allow access to pumps
liquid air trap for gauge
Knudsen gauge
bell jar
1"x16" steel plate
insulated terminals for filament
baffle to stop things from falling down tube
glass stop-cock inlet
discharge tube
3" pipe
3" valve
rubber hose 1" inside diam. 2" outside diam.
water cool-ing
pinch clamp
metal "T"
to drain
asbestos jacket
to mechanical pumps
pinch clamp
2½" oil diffusion pump with "polar cub" heater
6" oil-diffusion pump with flat spiral heater
Scale
6"
0
1 foot
2 feet

Fig. 4.

static vacuum system, since the system shown in Fig. 4 must be repeatedly opened. The recent development of fast oil diffusion pumps, which give the degree of vacuum required in spite of these obstacles, has been mainly responsible for the modern extensive use of this type of flexible vacuum system.

Diffusion pumps. Diffusion pumps will operate only if the pressure is less than a few tenths of a millimeter of mercury, and they operate best with a "backing pressure" of a few hundredths of a millimeter of mercury. The necessary "backing pressure" is obtained by mechanical pumps. The operation of a mercury diffusion pump is illustrated in Fig. 5. The pump shown here illustrates Langmuir's practical adaptation of Gaede's discovery of the principle of diffusion pumping.[20] The following explanation of its action applies as well to the action of oil diffusion pumps.

A stream of mercury vapor is obtained by heating liquid mercury in boiler B to a temperature of about 110°C. The vapor stream which effuses from the attached chimney is indicated by arrows. This stream forms a partition between chamber N and chamber M. The vapor finally condenses on the water-cooled walls of chamber N and returns under the influence of gravity to the boiler as a liquid. Gas molecules in chamber N which diffuse into the vapor partition have a small chance of penetrating it and entering chamber M. Rather, it is more probable that they will be carried by the stream back into chamber N. However, gas molecules in M which diffuse into the vapor

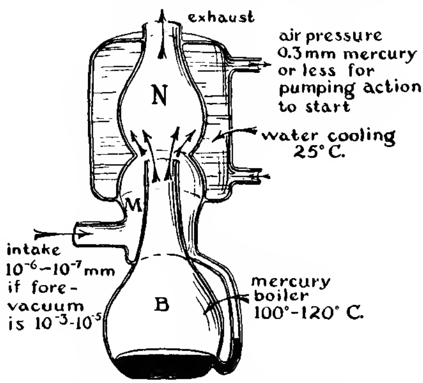


Fig. 5. Diagrammatic sketch of Langmuir's diffusion pump.

[20] Langmuir, I., *Phys. Rev.*, *8*, 48 (1916).
Gaede, W., *Ann. d. Physik*, *46*, 357 (1915).

partition are carried along by molecular bombardment into N, where they are removed by the mechanical pump.

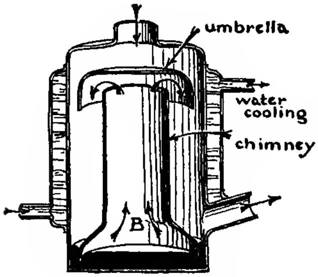


Fig. 6. Langmuir's umbrella pump.

The pressure in N must exceed that in M by a factor of the order of 100 if the rate of diffusion is to be the same in both directions across the vapor partition. Where N is evacuated by an auxiliary diffusion pump instead of the mechanical pump, pressures of 10^{-7} mm of mercury or lower can be obtained in a tight glass apparatus connected to M (provided mercury vapor is removed with a liquid air trap).

Mercury pumps have been studied by many investigators.[21] Figs. 6 to 12 are representative of the designs which have evolved as a result of these studies. We will not discuss these pumps in detail, as we are mainly interested in this chapter in kinetic vacuum systems and oil diffusion pumps. With oil pumps it is not uncommon to have pumping speeds of some tens or hundreds of liters per second, whereas with mercury diffusion pumps the speeds are ordinarily only a fraction of a liter per second up to a few liters per second.

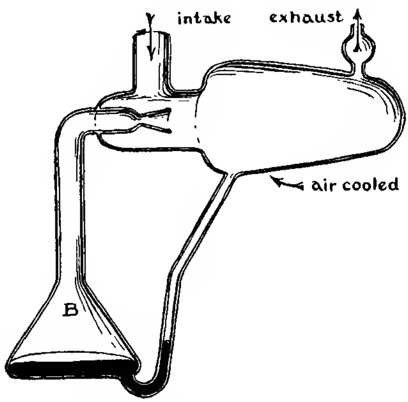


Fig. 7. Crawford's diffusion pump.

[21] Crawford, W. W., *Phys. Rev.*, *10*, 558 (1917).
Klumb, H., *Zeits. f. techn. Physik*, *17*, 201 (1936).
Molthan, W., *Zeits. f. techn. Physik*, *7*, 377, 452 (1926).
Stintzing, H., *Zeits. f. techn. Physik*, *3*, 369 (1922).
See the references to vacuum technique given in footnote 1, page 93, and other references cited herein. See also catalogues of E. Leybold Nachfolger.
Gaede, W., *Zeits. f. techn. Physik*, *4*, 337 (1923).
Ho, T. L., *Rev. Sci. Instruments*, *3*, 133 (1932); *Physics*, *2*, 386 (1932).

The use of oils as diffusion pump liquids. There have been many attempts to find a substitute for mercury as a pumping medium, for the use of mercury has one considerable disadvantage, namely, its vapor pressure is so high that traps are required to prevent it from diffusing into the vacuum system and destroying the vacuum. These traps, having a high resistance to the flow of gas, choke the pump. The only widely used substitutes for mercury are oils. The oils used for this purpose are either especially refined petroleum oils of the naphthene type as developed by C. R. Burch,[22] or they are organic compounds such as butyl phthalate as developed by Hickman and Sanford[23] of the Eastman Kodak Laboratories. Recently, Hickman has recommended a new synthetic organic oil called Octoil, which is claimed to be superior to butyl phthalate.[24] Oils of the type developed by Burch are manufactured under Metropolitan Vickers' patents under the trade name of Apiezon oil.[25] Similar oils are now available in this country which yield pressures below 10^{-6} mm of mercury.[26]

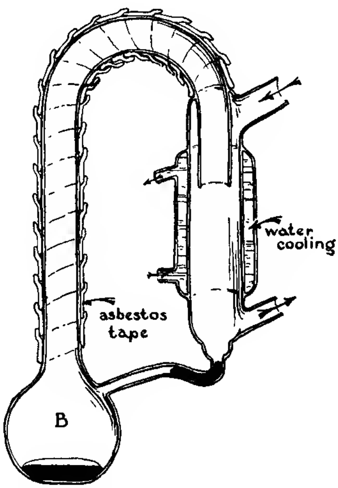


Fig. 8. Down-jet diffusion pump.

Oil pumps have the advantage over mercury pumps that they do not require traps except in certain applications.

[22] Burch, C. R., *Nature*, *122*, 729 (1928); *Roy. Soc., Proc.*, *123*, 271 (1929).
[23] Hickman, K. C. D., and Sanford, C. R., *Rev. Sci. Instruments*, *1*, 140 (1930).
[24] Hickman, K. C. D., *Frank. Inst., J.*, *221*, 215, 383 (1936).
[25] This oil may be obtained from the James G. Biddle Company, Philadelphia, Pennsylvania.
[26] Relative to pump oils see the following:
von Brandenstein, Maruscha, and Klumb, H., *Phys. Zeits.*, *33*, 88 (1932).
Klumb, H., and Glimm, H. O., *Phys. Zeits.*, *34*, 64 (1933).
These oils may be obtained from Litton Laboratories, Redwood City, California, and the Central Scientific Company, Chicago, Illinois.

Another advantage is that oil pumps may be fabricated either from steel or from brass and copper, whereas metal mercury pumps must be constructed of steel with welded joints. Brass and copper pumps can be assembled with soft solder, except for the boiler and chimney, where it is advisable to use silver solder. Aside from the questions of traps and construction, the contrast between oil and mercury pumps is less distinct. Oil pumps without traps do not give quite as low a limiting pressure as trapped mercury pumps, although their speed may be many times greater. If traps are used, there is probably little difference between the limiting pressures attainable. Oil pumps have the advantage that a baked-out total obstruction charcoal tube at room temperature is as effective as a liquid air trap. However, the use of a total obstruction charcoal trap sacrifices the higher pumping speed of the oil pump.

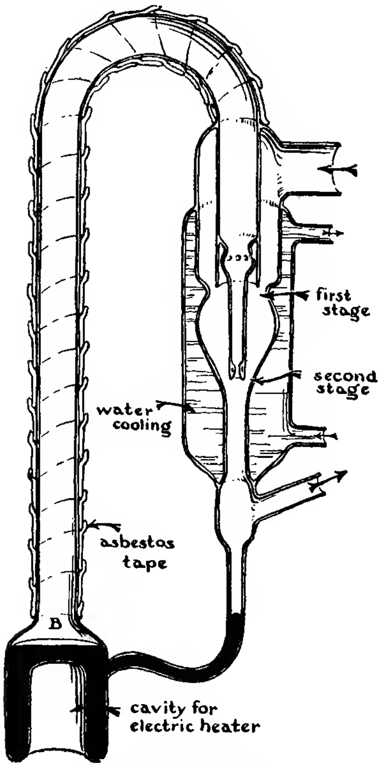


Fig. 9. Kurth's two-stage mercury diffusion pump.

It is not advisable to use a single oil pump. One should use at least two oil pumps in series. The second pump serves to keep the oil in the first purified. The limiting pressure is about tenfold lower when a second pump is used. Because mercury pumps will operate against a slightly higher back pressure than oil pumps, there are many cases in which a single mercury diffusion pump is adequate.

Oil diffusion pumps. Oil diffusion pumps are like mercury diffusion pumps in several respects. They have the same functional elements—a boiler to vaporize the oil and a chimney for conducting the vapor to the jet. The two types of pumps are also similar in the way in which they function. The oil vapor is projected from the jet across the throat of the pump and condenses on the cooled walls which form the outer boundary of the throat; and the condensed oil drains from the condensing surface back into the boiler by gravity. The vapor jet may be arranged in several ways: It may be directed upward as in the up-jet mercury pump shown in Fig. 5, it may be directed downward as in the umbrella down-jet mercury pump shown in Fig. 6, or it may project laterally as shown in Fig. 7.

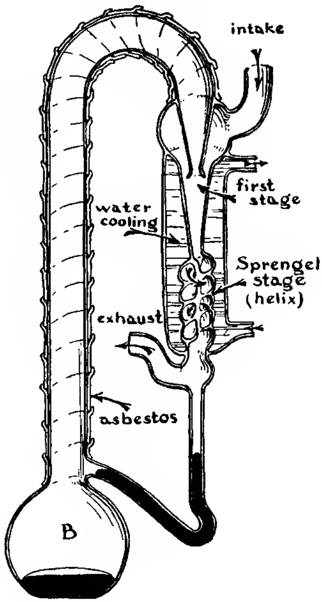


Fig. 10.

Although oil and mercury diffusion pumps have the same functional elements, they differ in the details of construction. The construction of oil diffusion pumps can be carried out in an ordinary machine shop. The important considerations for proper construction are outlined below:

1. The oil is decomposed slightly at the working temperatures of the boiler. This decomposition is accelerated by the higher temperature necessary when the cross section of the boiler is not large enough to afford an adequate surface from which to create vapor, or when the chimney and jet are not ample to deliver the required amount of vapor without an excessively high pressure drop.

2. Since oil has a low latent heat, the pump should be designed so that the heat required to maintain the working

temperature of the chimney and jet is supplied by conduction from the heater rather than by condensation of oil vapor. Naturally, copper is the best material for constructing the chimney on account of its large heat conductivity.

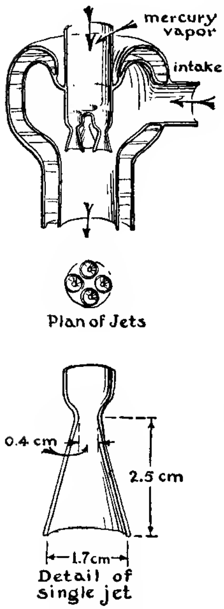


Fig. 11.

3. The decomposition of the oil is catalyzed by copper and brass and not by nickel. Accordingly, all parts of the pump exposed to the hot oil should be nickel-plated.[27]

4. The amount of oil decomposed in a given time is proportional to the amount of oil present in the boiler. It is, therefore, advisable to have only a shallow layer of oil in the boiler.

5. At least two single-jet pumps in series should be used. Multiple-jet pumps are not recommended because of the difficulty of regulating the flow of vapor to the various jets and of supplying the necessary amount of vapor required by them without an excessive boiler temperature.

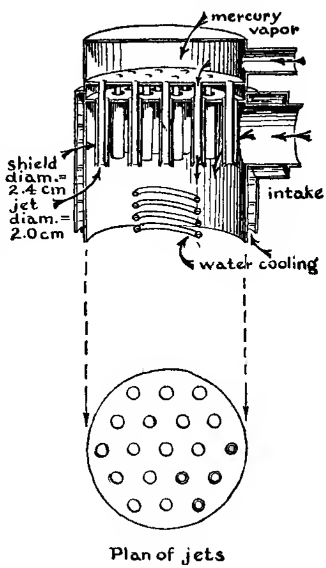


Fig. 12.

6. Throat clearances narrower than $\frac{1}{8}$ inch are practical only for up-jet pumps. Condensed oil will bridge gaps of this narrowness in pumps of the down-jet type.

7. Backward evaporation of the oil into the pumping line should be restrained by the use of baffles.

[27] Privately communicated: Charles V. Litton, Engineering Laboratories, Redwood City, California.

8. Cold oil is a better solvent for many gases and vapors than hot oil. Accordingly, the condensed oil should be returned to the boiler at the maximum temperature possible. Otherwise, a certain amount of the exhaust gases and vapors dissolve in the condensed oil and contaminate it.

9. The use of electric heat for the boiler is advisable, since it is subject to more delicate control than gas heat. A Calrod heater unit, such as used in electric stoves, can be re-coiled into a helix of 2 inches in outside diameter or as a flat spiral of smaller dimensions.

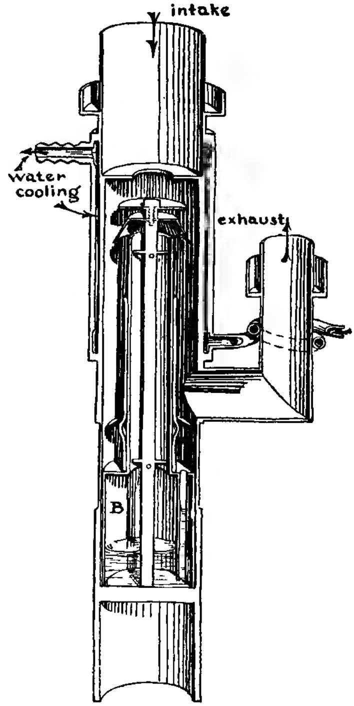


Fig. 13.

Figs. 13 to 18 illustrate several oil pumps which are currently popular.[28] The pump shown in Fig. 13, designed by Sloan, Thornton, and Jenkins, satisfies the requirements for good design outlined above and at the same time combines these features together with simplicity of construction. The following description of this pump is a quotation from a paper of Sloan, Thornton, and Jenkins.[29]

The Apiezon oil diffusion pump was originally developed by the Metropolitan Vickers Company in England for this very pur-

[28] References to pumps having interesting construction but not represented here include the following:

Copley, M. J., Simpson, O. C., Tenney, H. M., and Phipps, T. E., *Rev. Sci. Instruments*, *6*, 265, 361 (1935).

Esterman, I., and Byck, H. T., *Rev. Sci. Instruments*, *3*, 482 (1932).

Ho, T. L., *Rev. Sci. Instruments*, *3*, 133 (1932); *Physics*, *2*, 386 (1932).

[29] Sloan, D. H., Thornton, R. L., and Jenkins, F. A., *Rev. Sci. Instruments*, *6*, 80 (1935).

pose of continuously exhausting radio tubes. The oil is sold commercially in this country.

Fig. 13 is typical of the simplified designs which have been widely adopted in this country. The outer shell 2″ in diameter consists of a water-jacketed brass cylinder with a copper plate silver-soldered into its bottom. In the cavity beneath the bottom plate is placed an electric heater which boils the Apiezon "B" oil at less than 200°C in the chamber above. The oil vapor rises through the copper chimney and is deflected downward by a spun copper umbrella. The $\frac{5}{16}$″ clearance between the edge of the umbrella and the condensing wall is not critical, although an optimum exists for any specified set of pressures. Around the chimney is a glass heat shield, and a metal baffle plate to retard the rise of oil vapor from the roof of the boiler, but these can be omitted without serious consequences. The two baffles above the umbrella prevent the escape of oil vapor directly into the region being evacuated. The convenient baffle system shown here reduces the speed of the pump to less than half, so that its overall speed is only thirty liters per second. This is more than sufficient for these oscillator tubes, since the connecting system reduces the speed to less than ten liters per second. A pressure in the oscillators of 10^{-5} mm is sufficient.

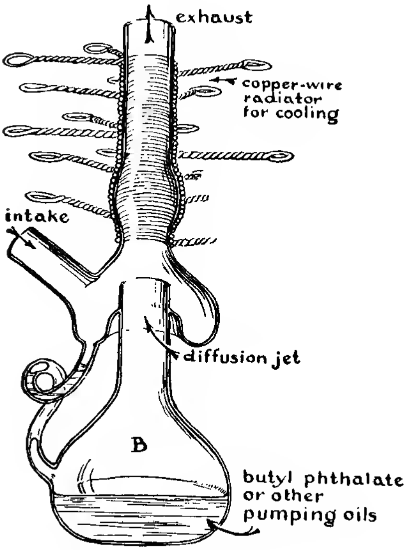


Fig. 14.

Incidentally, the same general design is also well suited to larger pumps of 4″ and 6″ diameter, for use with larger tubes. The speed of an oil pump can be greatly increased by enlarging the diameter of the overhead region which contains the baffles necessary to guard against escaping oil vapor.

A 2-inch pump of such construction will have a pumping speed of about 30 liters/sec., or a speed factor slightly greater than 50 per cent.

If such a high speed is not needed, an up-jet pump may serve. Fig. 14 shows Hickman and Sanford's all-glass design of an up-jet pump.

Fig. 15 shows an all-metal up-jet pump designed by Edwin McMillan.[30] With the boiler temperature adjusted to give maximum pumping speed, this pump will work at a rate of 4 liters/sec. against a backing pressure of $\frac{1}{2}$ mm of mercury. If the boiler temperature is too high, the action of the pump will be erratic, since returning condensed oil interferes with the vapor jet.

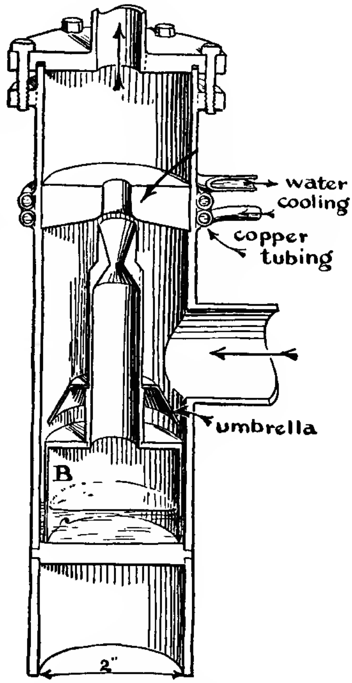


Fig. 15. McMillan up-jet pump. Hole in upper block (indicated by arrow) $\frac{1}{4}$ inch in diameter. Outside diameter of jet $\frac{9}{32}$ inch. Jet clearance $\frac{3}{32}$ inch. The necessary baffles above the jet are not shown.

A design combining glass and metal construction, developed by Joseph E. Henderson,[31] is shown in Fig. 16. He reports this pump to be capable of working against a backing pressure of a few tenths of a millimeter pressure in contrast to the pressure of about $\frac{1}{100}$ mm required for oil pumps with a throat opening of $\frac{1}{8}$ inch or more. Pressures as low as 10^{-8} mm of mercury were obtained with it when it was operated with a charcoal trap.

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[30] Privately communicated.

[31] Henderson, Joseph E., *Rev. Sci. Instruments*, *6*, 66 (1935).

A pump designed by Zabel with a novel oil heater added by James A. Bearden[32] is shown in Fig. 17. The advantage of a pump of this design is that it quickly starts working after the heater is turned on.

More recently, K. C. D. Hickman and others have experimented with pumps in which the oil is continually purified.[33] Pumps of this type are particularly suitable for work with gases and vapors which dissolve in the oil or decompose it. Fig. 18 shows a pump which incorporates some of the results of Hickman's investigations.

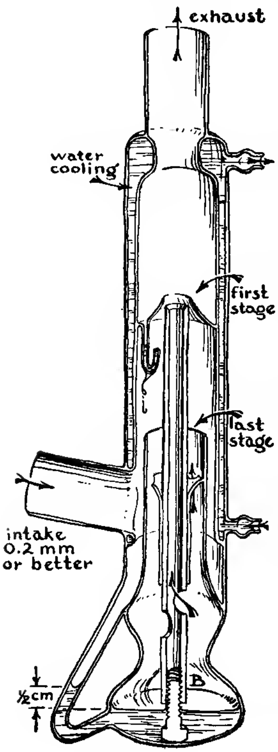

Fig. 16.

Mercury traps. Mercury vapor diffuses from a mercury diffusion pump into the exhausted vessel unless it is removed in a trap by condensation on a cold surface. Besides the inconvenience and expensive necessity of requiring a refrigerant, the use of traps has the more serious result of choking the pump. This is especially true for big mercury pumps of high speed. For example, a mercury pump with a speed of several hundred liters per second at its throat may have an effective speed beyond the trap of only several tens of liters per second.

The common trap designs for condensing mercury and water vapors are illustrated in Fig. 19. Type *A*, the simplest, is frequently used for trapping the vapors from a McLeod gauge. It is also useful in conjunction with an ionization or Pirani gauge for hunting leaks. Type *B*, the most

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[32] Bearden, J. A., *Rev. Sci. Instruments*, *6*, 276 (1935).
Zabel, R. M., *Rev. Sci. Instruments*, *6*, 54 (1935).
[33] See footnote 24, page 113.

common type, may be conveniently constructed from metal and a simple glass tube as shown at B', or it may be

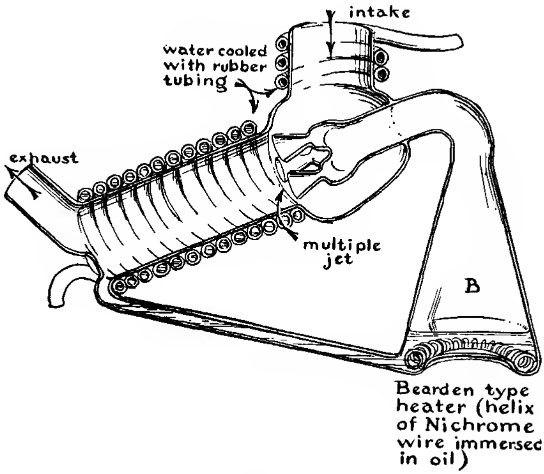

Fig. 17.

constructed as shown at B'' with a separator or baffle to cause the gas to circulate against the cold walls of the glass tube. Both types *A* and *B* are immersed in the refrigerant liquid. Types *C*, C', and C'' contain their own refrigerant, but because of inferior heat insulation these traps are less economical to keep cold.

As refrigerant liquids for trapping mercury and water vapor, either liquid air or dry ice in acetone may be used. The temperature of the former varies from −190°C. to −183°C., depending on the extent to which the nitrogen has been boiled out of the liquid air, leaving liquid oxygen.

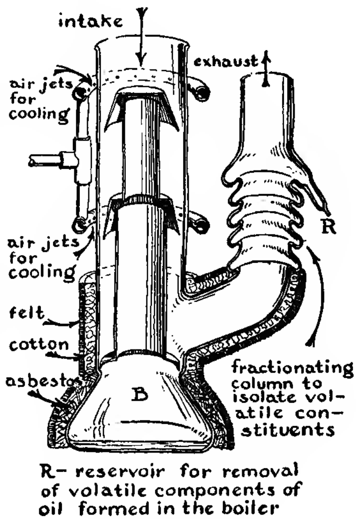

Fig. 18.

The temperature of dry ice–acetone mixture is about $-78°C$. At the temperature of liquid air the vapor pressure of mercury is 1.7×10^{-27} mm, while at $-78°C$. it is 3.2×10^{-9} mm. For trapping water, liquid air temperatures are sufficiently low. However, since the vapor pressure of ice is about 10^{-3} mm at $-78°$, the dry ice–acetone mixture is not sufficiently cold to trap water vapor effectively. Accordingly, when this refrigerant is used for mercury, it is necessary at

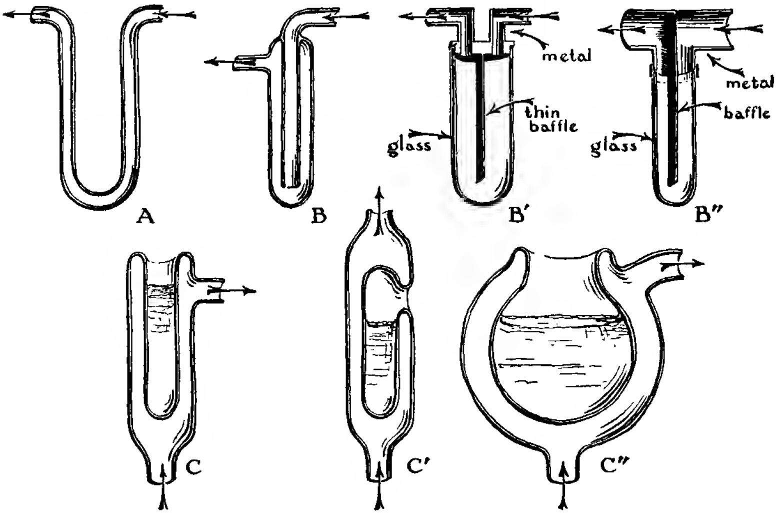

Fig. 19.

the same time to expose anhydrous phosphorus pentoxide in the vacuum in order to remove the water vapor.

The vapor pressure of the vacuum pump oils used in roughing pumps, according to Dushman, is 10^{-3} to 10^{-4} mm at ordinary temperatures, $\frac{1}{5}$ of this value at 0°C., and negligibly small at the temperature of dry ice or liquid air.

Carbon dioxide is adequately trapped by traps cooled by liquid air, since its vapor pressure, at liquid air temperature, varies from 10^{-6} mm to 10^{-7} mm. Carbon monoxide, methane, ethane, and ethylene, having considerably higher vapor pressures, are not effectively trapped even by a liquid air trap.

Virtual leaks. Gases will condense when their partial pressure is above the vapor pressure corresponding to the trap temperature. (However, they will re-evaporate later when the pumps reduce the pressure to a sufficiently low value.) This condensation may give rise to a virtual leak if the trap is cooled too soon after the evacuation of a system is started. We use the term *virtual leak* because the system appears to have a leak, when it is, in fact, quite tight. As an example, consider a system with traps cooled with a dry ice–acetone mixture but with phosphorus pentoxide omitted. Some of the water vapor originally in the system, both in the air and from the walls where it is held adsorbed, will be condensed in the trap. As the evacuation of the system proceeds, the pressure will approach a limit of 10^{-3} mm, this being the pressure of the water vapor in the trap, and the system will exhibit all the "symptoms" of a leak. The same effect is encountered if liquid air is put on the system too soon. Some of the water vapor will condense on the upper regions of the trap walls, and as the liquid air level around the trap falls, owing to evaporation, the temperature of the water condensed as ice will rise until it begins to sublime, producing a virtual leak. On the one hand, these ice crystals are too cold to evaporate rapidly and be evacuated by the system (or colder regions of the trap), while, on the other hand, they are warm enough to degrade the vacuum. Likewise, gases like ethylene may condense in a trap cooled by liquid air and degrade the vacuum.

To avoid virtual leaks, the proper procedure is to keep the traps warm until a vacuum is obtained at which mercury begins to diffuse into the evacuated apparatus, that is, until a pressure of about 10^{-2} mm is obtained. Then the tip of the trap is cooled until the vacuum reaches its limit, P_0, and finally the trap is immersed in the liquid air to the full depth.

"Oil" traps. The vapor pressures of vacuum-pumping oils, such as Apiezon "B" oil, are very low, but gases produced by thermal decomposition of the oil may give rise

to some deterioration of the vacuum and necessitate the use of traps. For example, when Bearden evacuated an X-ray tube with the diffusion pump shown in Fig. 17, he found that a carbon deposit formed on the target of the tube.[34] He found, also, that the filaments of the tube deteriorated at an excessive rate. However, the use of a refrigerated trap greatly reduced these effects. The trap he used was cooled with dry ice in alcohol.

The trap shown in Fig. 20 was designed by Hickman for diffusion pumps which use Octoil.[35] According to him, it is sufficient to cool the trap with running water. Electric refrigerator units are sometimes used to trap vapors from oil pumps. These are, naturally, justified only in large and permanent installations.

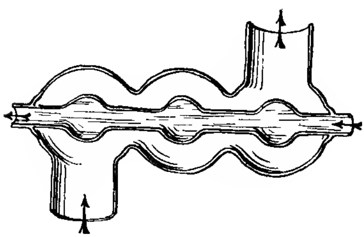

Fig. 20.

In ordinary experimental work, charcoal traps are satisfactory for use with oil diffusion pumps. Several charcoal trap designs are shown in Fig. 21. Of these, the total obstruction trap, *A*, is the most effective, although it has the highest resistance, *W*, for the gases passing through it. Becker and Jaycox suggested a trap of type *A*. They found that a charcoal trap removed oil and condensable vapors to such a degree that an ionization gauge indicated a "pressure" as low as 10^{-8} mm of mercury.[36] This has been confirmed by Joseph E. Henderson.[37]

When charcoal traps become charged with oil and vapors, it is necessary to bake them out. Becker and Jaycox observed that condensed pump oils are decomposed by baking them in contact with charcoal, and that the decomposition products are gases.

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[34] Bearden, J. A., *Rev. Sci. Instruments*, *6*, 276 (1935).
[35] See footnote 24, page 113.
[36] Becker, J. A., and Jaycox, E. K., *Rev. Sci. Instruments*, *2*, 773 (1931).
[37] Henderson, Joseph E., *Rev. Sci. Instruments*, *6*, 66 (1935).

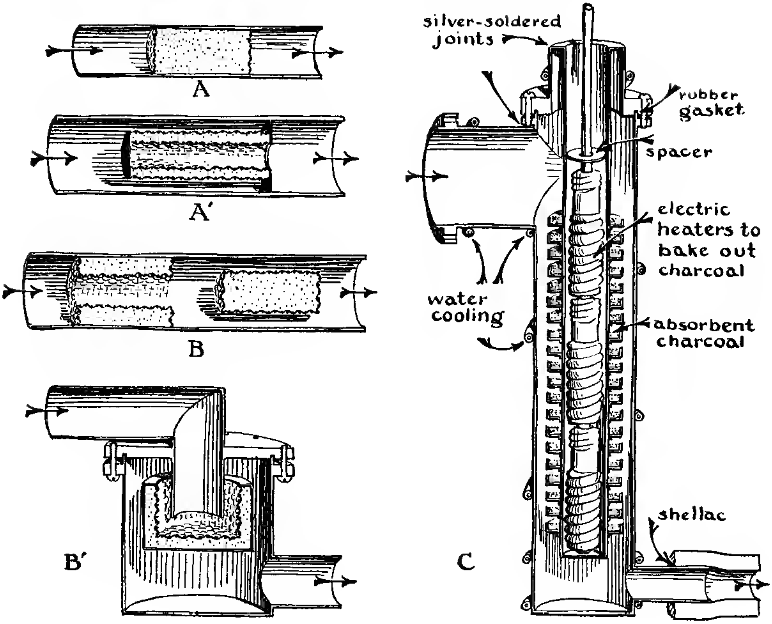

Fig. 21.

Construction of kinetic vacuum systems. Glass was formerly used extensively for the construction of vacuum apparatus, but now metal has replaced it for many uses. Glass as a construction material is characterized by its transparency, high electrical insulating quality, and by the fact that it is easily cleaned and may be baked out and sealed off to give a more or less permanent vacuum. Also, auxiliary parts can be welded to an apparatus without the use of any gaskets or sealing wax. These welds are easily tested for leaks with a spark.

Unfortunately, large and complicated apparatus is difficult to construct from glass. On the other hand, large vacuum systems made of metal are not fragile, and repairs and alterations on them can be easily made in the machine shop.

The metal most frequently used is yellow brass. A vacuum-tight apparatus can be made from plates and cylin-

ders of this metal, screwed together and "painted" on the outside with beeswax and rosin mixture; or the plates, cylinders, and so forth, may be fitted together with rubber or lead fuse-wire gaskets. The brass parts may also be soft-soldered or silver-soldered, depending on the temperature resistance and strength required.

Steel apparatus may be soft-soldered, silver-soldered, brazed, or welded. Electric welding is quite satisfactory for vacuum work if it is done in two or three "passes" with shielded electrodes. It is generally less subject to leaks than gas welding, and it does not warp the work as much. Steel vacuum tanks, especially if they are rusty, are sometimes coated on the inside with Apiezon wax "W" to stop leaks as well as to offer a surface which does not give off gas.

Since metal vacuum walls outgas more than glass, small leaks are more difficult to find. It is a common procedure to coat the outside of metal apparatus with lacquer, which seals small leaks and at the same time gives a workmanlike appearance to the apparatus. Glyptal is heat resistant. For example, it may even be used for coating the outside surfaces of diffusion-pump boilers.

Many things are exposed in kinetic vacuum systems which one would not expose in static vacuum systems. Chief among them are rubber (especially as used for gaskets), waxed packing, beeswax and rosin mixture, Apiezon wax, and ordinary machined metal parts which are not outgassed.

Wood, paints and varnishes, porous cements, and rust should not be exposed even in a kinetic vacuum system.

Rubber hose may be used for connections, and with a pinch clamp it serves as a venting device. Rubber should not be exposed to high vacuum if pressures of the order of 10^{-6} or less are desired.

Joints. Two tubes of glass or metal may be butt-joined by slipping a wide rubber band over them. The rubber surface, including the junctions of the rubber to the tubes, is painted with several coats of shellac as shown in Fig. 22. This type of joint is easily disconnected. For small tubes,

a short length of rubber hose makes a convenient connection. Rubber tape or strips of raw rubber may also be used. Inasmuch as rubber is somewhat permeable to some gases and gives off hydrogen sulphide and other vapors in vacuum, the connected tubes should always fit together neatly to decrease the area of rubber exposed. The joint may be first wrapped with sheet aluminum and then with rubber.[38] This procedure decreases the area of rubber exposed. If any considerable area of rubber is exposed, it is advisable to boil it in a 15 per cent caustic solution (potassium hydroxide or sodium hydroxide) to dissolve free sulphur and remove talc from its surface. It is then washed with water and dried, either with alcohol or by a vacuum pump.

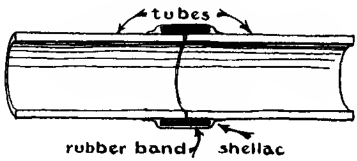

Fig. 22.

If rubber tubing becomes porous and checked with age, it should be painted on the outside with castor oil.

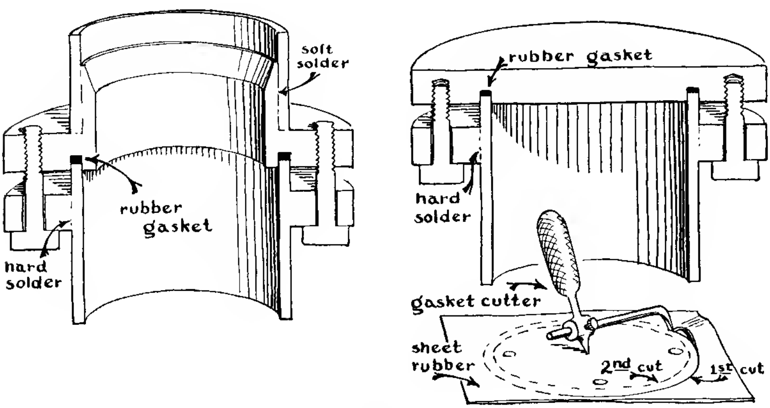

Fig. 23.

Two metal tubes may be joined with flanges which are sealed with a tongue and groove joint fitted with a rubber gasket as shown in Fig. 23. This construction is recom-

[38] The Central Scientific Company supplies a raw rubber tape for this. They recommend the use of a piece of thin aluminum sheeting with it.

mended where mechanical strength is desired and also where the joint must withstand moderate internal pressure. The tongue should have the same thickness as the groove to within a few thousandths of an inch, so that the rubber gasket will not extrude as the pressure for fitting the joint is applied. The gasket is cut from a sheet of packing with a cutter like the one shown. The rubber gasket is used dry, and if the tongue and groove have bright smooth surfaces, the joint is sure to be free from leaks. Furthermore, the joint exposes very little rubber surface to the vacuum system.

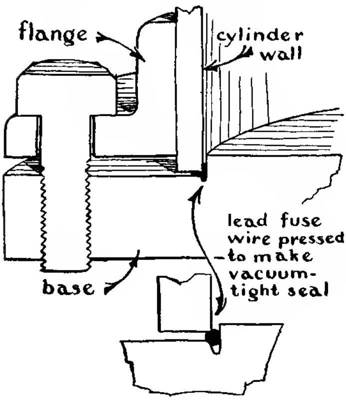

Fig. 24.

In another type of joint, shown in Fig. 24, a lead fuse wire can be used as a gasket instead of rubber. The gasket in this case is a loop of 20-ampere fuse wire, butt-welded by means of the heat from a match and a little soldering flux. The circumference of this loop is made slightly shorter than required and is stretched into the groove to make a snug fit. The pressure applied in the flange flows the lead into intimate contact with the two elements of the joint. Lead-wire joints can be used on systems to operate at elevated temperatures, since they will hold to higher temperatures than tongue and groove joints sealed with rubber. A lead gasket of this type is used on the 40-inch bell jar for aluminizing astronomical mirrors as shown in Fig. 13 of Chapter IV. This particular joint has been made more than a hundred times, and it has been consistently vacuum-tight. Aluminum wire holds to even higher temperatures.

Seals. It is frequently necessary to make a vacuum-tight seal between a glass bell jar and a metal base plate. Formerly, stopcock grease was used, applied to the foot of the bell jar. This type of seal was not always tight, and the grease

frequently entered the apparatus and contaminated exposed surfaces. A better procedure is to use wax instead of stopcock grease. The bell jar is set on the base plate, both the foot of the bell jar and the base plate being clean and dry. Beeswax and rosin mixture, smoking hot, is then applied with a medicine dropper to the outer edge of the bell-jar flange to effect the seal, as illustrated by Fig. 25. The bell jar can be removed from the base plate in the following manner: After scraping away the wax with a putty knife, loosen the jar by striking a sharp blow at the top with the palm of the hand or by driving a razor blade gently under the edge of the jar. If a metal bell jar is used, a recess may be provided so that the seal can be cracked by prying with a screw driver after as much of the wax as possible has been scraped away.

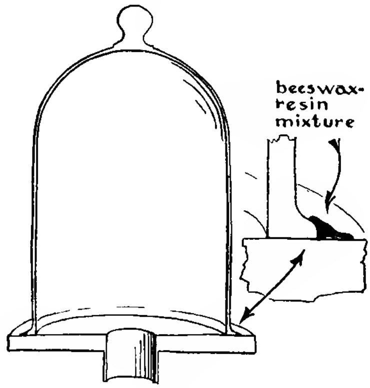

Fig. 25.

Windows may be sealed over observation ports in a similar manner. The wax is applied with the medicine dropper, and the seal is effected without sensibly heating either the port or the window.

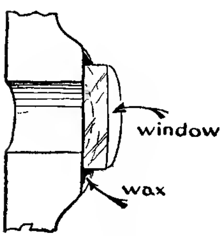

Fig. 26.

Windows may be sealed with hard wax. It is necessary to heat both the port and the window to temperatures above 100°C. when hard waxes such as Apiezon "W," Picein, shellac, or DeKhotinsky wax are used. First the window and port are carefully cleaned, and then the window is clamped in the desired position. After being heated to the required temperature, the wax is applied to the outside edge of the window, from where it will be drawn between the window and the port by capillary force. The wax drawn

under the window forms a thin bonding layer of large area, which exposes a minimum surface of wax to the vacuum. (See Fig. 26.)

Fig. 27 shows the procedure for sealing two glass tubes together with Picein wax to form a butt joint or telescope joint. The procedure here is to wrap a soft strip of Picein around the warmed glass tubes. This strip is molded from a stick of wax after it is thoroughly softened. The stick of wax is softened by alternately heating it in a Bunsen flame until its surface is liquid and withdrawing it to cool until its surface solidifies. When the strip is ready and while it is still soft it is wrapped around the warmed joint and molded as shown in Fig. 27. The wax will not stick to the fingers if they are damp. After the glass and wax are cool, a flame is applied to fuse the wax superficially and insure tangential contact to the tubing.

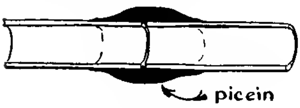

Fig. 27.

Electrodes. In the chapter on glass blowing, we discussed the construction details for leading electrical conductors into glass apparatus. In a kinetic vacuum system, electrodes are usually fastened through holes in a metal wall. Construction details are shown in Fig. 28 for high-current conductors and in Fig. 29 for high-potential conductors. The high-current conductor or electrode consists of a brass screw bolted into the vacuum wall, the head and body of the screw being insulated from the metal vacuum wall with mica. After the insulation has been tested with a lamp, the whole assembly is made vacuum-tight by coating the screwhead, insulation, and the local area of the outside

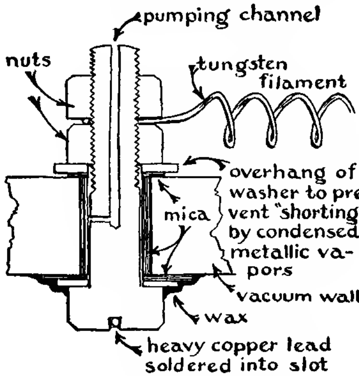

Fig. 28.

surface of the vacuum wall with beeswax and rosin mixture or with glyptal lacquer. Beeswax and rosin mixture is used if the operation temperature is about room temperature. Glyptal, after baking to polymerize it, is used for operation temperatures up to about 100°C.

The electrode just described does not have high insulating qualities. Where better insulation is needed, a capillary glass tube is used in either of the ways shown in Fig. 29. In either case the electrode is easily removable for cleaning off condensed metallic vapors, for replacement of the glass,

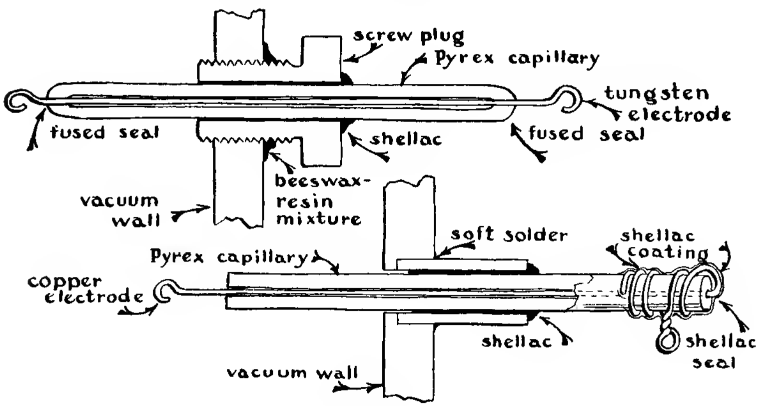

Fig. 29.

and so forth. If the conductor wire is tungsten, it may be sealed directly to the Pyrex capillary. The capillary, with its central conductor, is first sealed in a bored machine screw with pure shellac or DeKhotinsky wax. This is then screwed through the walls of the vacuum system and made tight with beeswax and rosin mixture applied on the outside.

Valves. Valves are used on the low-vacuum side of diffusion pumps to prevent oil in the mechanical pumps from flowing into the other parts of the apparatus. Between the diffusion pumps and the apparatus, large valves are useful to allow by-passing the diffusion pumps. For example, in the vacuum system shown in Fig. 4, a large 4-inch valve makes it possible to open up the main vacuum chamber

and re-evacuate it without destroying the vacuum in the diffusion pumps. Valves between various parts of a large vacuum system facilitate narrowing the search for leaks, since one part after another can be isolated.

The simplest valve for venting a vacuum system is a short length of rubber hose and a pinch clamp. Rubber vacuum hose is now available in sizes up to 1 inch in diameter.[39] This large hose may be used in short lengths on the high-vacuum side of the diffusion pump when the pumps have a high capacity and when a vacuum of only 10^{-4} is desired. Usually, however, it is advisable to confine the use of rubber hose to the low-vacuum side of the diffusion pumps.

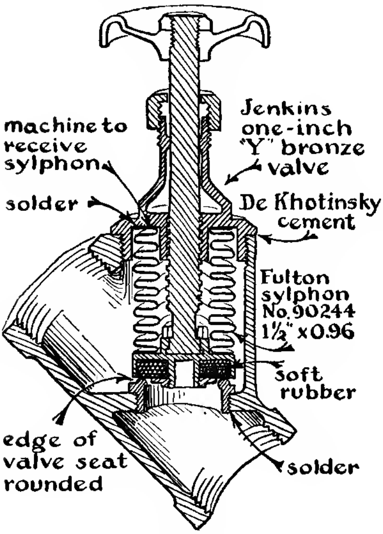

Fig. 30.

Ordinary plumbing valves can be modified for use in high-vacuum work. The glands are repacked with twine soaked in Apiezon compound "Q," beeswax, stopcock grease, or universal wax. Since the rubber gaskets supplied in these valves are often too hard for vacuum work, it is necessary to replace them with softer rubber. It is advisable to make a new end for the valve so that the new gasket rubber can be retained in a groove. The outside of the valve may be painted with shellac or glyptal lacquer as insurance against leaks, it may be coated with Apiezon wax "W," or it may be tinned. DuMond and Rose have described valves equipped with a sylphon bellows as a substitute for a packing gland.[40] This is illustrated in Fig. 30. A packless valve of this type

[39] Small hose is obtainable from scientific supply houses. Large sizes of vacuum hose are sold by Central Scientific Company, Chicago, Illinois.

[40] DuMond, J. W. M., *Rev. Sci. Instruments*, *6*, 285 (1935).
Rose, John E., *Rev. Sci. Instruments*, *8*, 130 (1937).

manufactured by the Hoffman Company can be readily adapted to vacuum work as shown in Fig. 31.[41]

Ordinary stopcocks can be sealed with stopcock grease for use in a high-vacuum system. Stopcock grease is made by digesting 1 part pale crepe rubber cut in small pieces with 1 part Apiezon compound "M." This digestion is carried out in a balloon flask with prolonged mechanical stirring at an elevated temperature obtained by means of a water or steam bath.

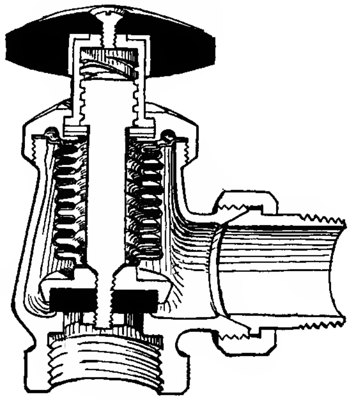

Fig. 31. Hoffman packless valve.

When it is necessary to avoid grease on a stopcock, bankers' sealing wax, Apiezon wax "W," or Picein can be used.[42] Of these waxes, Picein exhibits the best body. With any one of them the valve is warmed until the wax becomes plastic each time that it is turned. (See Fig. 32.) Stopcocks may be lubricated with dry graphite and sealed with mercury.

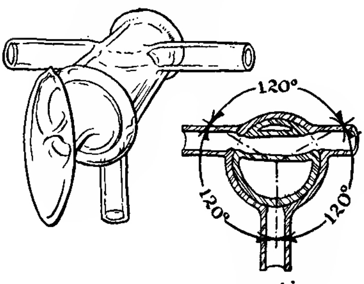

Fig. 32. Zaikowsky stopcock. U. S. Patent 2000552.

Mechanical motion. Mechanical motion can be introduced into a vacuum system through nonferrous vacuum walls with a magnet. An armature or bar magnet is fastened to the moving part inside the system and actuated by an electromagnet outside. The armature can be hermetically sealed in a glass tube to avoid outgassing.

[41] Hoffman Specialty Company, Waterbury, Connecticut. Crane and Company are local agents.

[42] For a description of a greaseless valve using a silver bellows acting against a silver chloride seat, see Ramsperger, Herman C., *Rev. Sci. Instruments*, *2*, 738 (1931).

A metal bellows can be used to introduce the reciprocating or oscillating motion of a lever.[43] When the end of the lever executes a circular motion, this motion can be transformed into rotation inside the vacuum.

Van de Graaf has developed the high-speed sealed shaft shown in Fig. 33. The packing used is Apiezon grease "M" charged with graphite, and the pumping action of the right- and left-handed screws, cut on the shaft, prevents the extrusion of the packing compound.

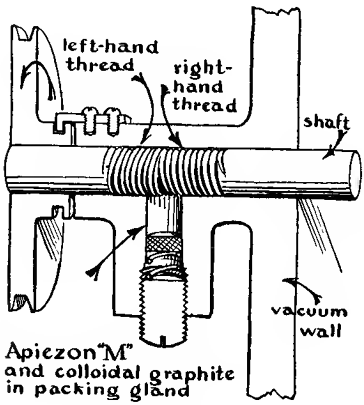

Fig. 33.

Mechanical motion can be introduced through an ordinary packing gland packed with cotton twine soaked in Apiezon compound "Q" as shown in Fig. 4.

Leaks. In planning a metal vacuum system, a part of the construction cost should be set aside to provide suitable fittings, plugs, plates, and tie bolts. The use of these makes it possible to pump air or hydrogen into separate compartments of the apparatus until the pressure is 50 or 100 lbs./square inch. For detecting leaks the pumped-up compartment is submerged in water or painted with liquid-soap solution. Hydrogen, which may be used instead of air to pump up the apparatus, has the advantage over air that it diffuses through small holes approximately four times faster. When leaks are found, they may be repaired by welding or soldering or by merely peening the surface. After the whole apparatus is put together, the outside of the system is coated with several layers of glyptal varnish, alternating the color of the varnish coats, say blue and red, to facilitate complete coverage with each one of them. If possible, the coating is baked at a temperature of about 120°C.

[43] Brose, H. L., and Keyston, J. E., *Journ. Sci. Instruments*, 7, 19 (1930).

Leaks are usually found in a glass apparatus by passing the ungrounded high-potential electrode of a spark coil or high-frequency coil over the surface of the glass. When the electrode comes near the leaking channel, a spark jumps to it and causes residual gas inside the apparatus to become luminous. As a safety precaution, a spark gap of $\frac{1}{4}$ to $\frac{1}{2}$ inch should be connected in parallel with the electrode and the ground to prevent an excessive potential which might puncture the glass.

Leaks in metal apparatus which are not detected by immersing the apparatus in water or painting it with soap solution are more difficult to locate. In general, the procedure for finding them involves covering the walls of the apparatus with a liquid which solidifies, with water, or with a gas. In any case, while the search is in progress, the apparatus is maintained at the lowest pressure possible.

If a liquid covering is used, it is applied to local areas in progression until the offending region is located. As covering one may use a molten mixture of beeswax and resin, or it may be a thick solution of either shellac in alcohol or glyptal lacquer brushed on the walls, or it may be cellulose acetate solution sprayed on the walls. When a solution of shellac (or lacquer) is applied to the outside of a leaking channel, the solution is drawn into the channel by the vacuum. As the solvent evaporates from this solution into the vacuum chamber, the liquid in the channel congeals. Thus, the leaking channel is, in effect, filled with a solid shellac core. The amount of solvent passing into the vacuum through this core is negligible in cases where the procedure is suitable.

When the leak is covered with the solution, the vacuum usually improves at once. This improvement may be indicated by the disappearance of luminosity in a connected discharge tube and finally by sparking across an alternate gap. If an ionization or Pirani vacuum gauge is used, covering of the leak is indicated by motion of the spot of light on the scale of the instrument.

The general region in which leaks are located may be determined by temporarily covering the region with water. As the vapor pressure of water is only about $\frac{1}{30}$ of an atmosphere, the leak may be expected to be attenuated 30-fold when it is covered.

The third procedure for finding leaks involves covering general regions of the apparatus with gas, carbon dioxide for the top parts, since it is heavier than air, and illuminating gas for the bottom. Webster has described the use of a rubber "coffer dam" to facilitate the management of the gas.[44] Illuminating gas may be blown on various parts of the apparatus from a hose, or the surface may be gone over with a wad of cotton wet with ether. Evidence that the leak is admitting gas instead of air is a change in character of the luminescence in a discharge tube connected to the apparatus or a change in reading of a vacuum gauge separated from the apparatus by a liquid air trap.

There are two procedures for using a discharge tube with illuminating gas, carbon dioxide, or ether. By the first, the obtainable vacuum is necessarily so poor, on account of the leak, that a distinct discharge is obtained. When the leak is covered, the luminosity in the positive column changes from the brownish-red color characteristic of air to the bluish-green of carbon dioxide or to the white of gas and ether. By the second procedure, used when the leak is small and a lower pressure is attainable in the system, the luminosity in the discharge is feeble. Webster suggests connecting the discharge tube behind one of the diffusion pumps as shown in Fig. 4. The backing pumps are then shut off, preferably just behind the discharge tube connection. The diffusion pump compresses the gas which the leak may be admitting, resulting in a more brilliant luminescence in the discharge tube.

A liquid air trap may be connected between the apparatus and a vacuum when carbon dioxide or other condensable gases are used. With this arrangement, when the leak is

[44] Webster, D. L., *Rev. Sci. Instruments*, *5*, 42 (1934).

admitting carbon dioxide, the trap condenses this gas, thus preventing it from entering the gauge. At the same time air and other gases which do not condense in the trap are removed by the pumps. As a result, even though the pressure in the system may have increased, an improvement of the vacuum is indicated.

Obviously, a gauge which reads continuously (Knudsen, Pirani, or ionization gauge) is preferred to a McLeod gauge for hunting leaks. Relative rather than absolute readings of the pressure are sufficient for locating leaks. Thus, the Pirani and ionization gauges are satisfactory, although they do not give absolute pressure determinations.

Vacuum gauges. A vacuum gauge determines the pressure in an evacuated apparatus by a measurement of some physical property of the residual gases, such as viscosity, heat conductivity, and so forth. The measurement of the response of a gauge to the residual gas naturally becomes more delicate as the gas becomes more and more tenuous. Finally, below a certain pressure limit (which is characteristic of a given gauge) the gauge does not behave measurably different from what it would if the vacuum were perfect. For example, a discharge tube will give qualitative indications of pressure down to about 10^{-3} mm of mercury. Below this pressure the tube becomes nonluminous and nonconducting. The characteristic limits for some of the other gauges are as follows:

Ionization gauge	10^{-9} mm of mercury
Knudsen gauge	10^{-6} mm of mercury
McLeod gauge	10^{-6} mm of mercury
Pirani gauge	10^{-5} mm of mercury
Langmuir's viscosity gauge	10^{-5} mm of mercury

The operation of the McLeod gauge depends on a definite volume of residual gases being compressed, so that as the volume decreases, the pressure is increased to a value at which the hydrostatic head of mercury can be measured with an ordinary scale.

The ionization gauge measures with a galvanometer the positive ions that are formed in an electric field when the

residual gas is bombarded with electrons. The Langmuir gauge depends on the measurement of viscosity, and the Pirani gauge on the measurement of heat conduction of the residual gas. The Knudsen absolute manometer measures the momentum transferred from a hot to a cold surface by the gas molecules.

Of the above gauges, only the McLeod and Knudsen are absolute manometers in the sense that their geometry and other measurable characteristics of construction and operation determine their response at a given pressure. The McLeod gauge is the simplest and most reliable for permanent gases, but it has the disadvantage of giving erratic response or no response at all to water vapor, carbon dioxide, ammonia, and pump oil vapors which adsorb on the walls of the gauge or condense to a liquid. This disadvantage is serious, inasmuch as water vapor, carbon dioxide, and so forth are often of importance in the last stages of obtaining a high vacuum. The Knudsen gauge responds to gases and vapors alike.

The response of an ionization gauge is difficult to predict from its construction details, and it must be calibrated with a McLeod gauge using permanent gases. Furthermore, before the pressure can be inferred, it is necessary to make corrections for the molecular weight of the gas and also for the possibility that the gas may be dissociated by the electron bombardment. Quantitative application of the gauge is unreliable to the degree to which these corrections are uncertain. Likewise, the response of the Pirani gauge depends on the molecular weight of the residual gas, and it must be calibrated with a McLeod gauge that uses permanent gases. The same is true for the viscosity gauge.

The McLeod gauge.[45] Although many improvements have been made in the McLeod gauge, they have seldom been applied. The gauge as ordinarily used today is essentially

[45] Gaede, W., *Ann. d. Physik*, *41*, 289 (1913).
Hickman, K. C. D., *J.O.S.A.*, *18*, 305 (1929).
Pfund, A. H., *Phys. Rev.*, *18*, 78 (1921).

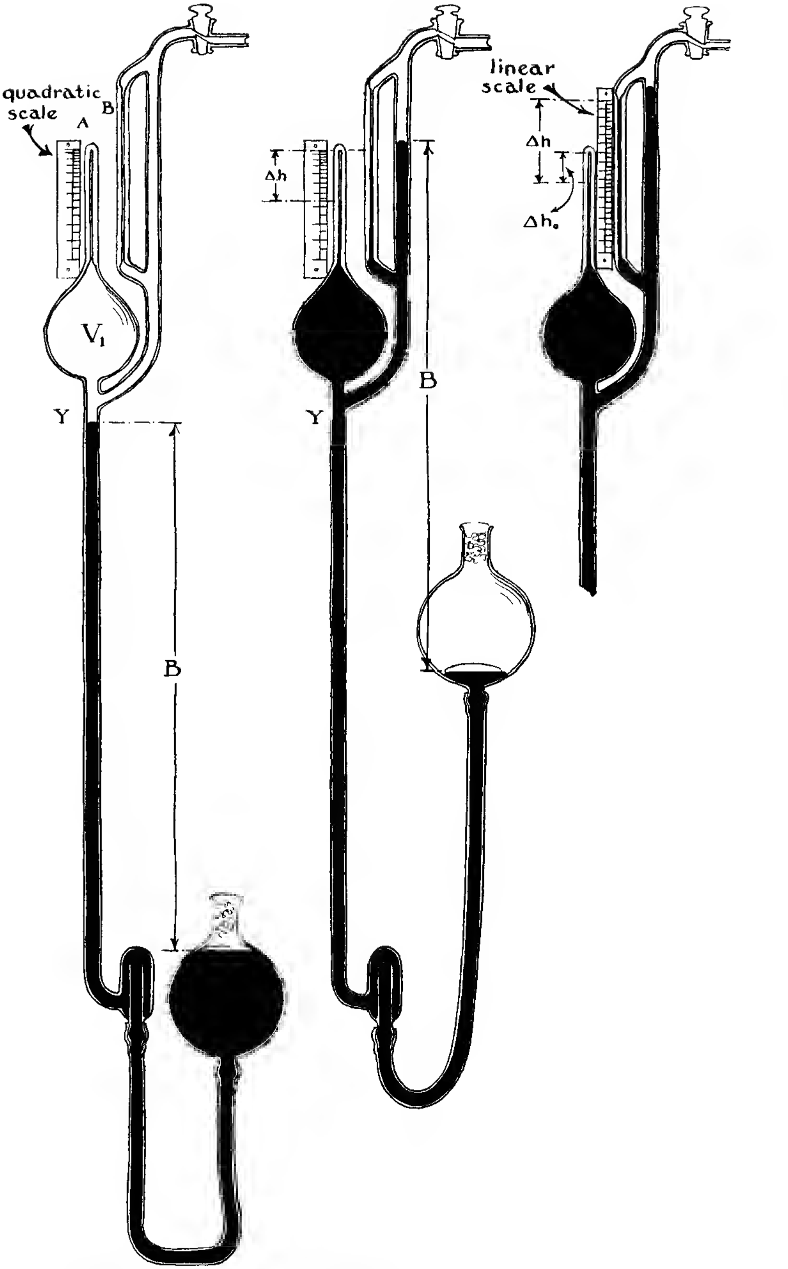

Fig. 34.

the same as it was originally. We will discuss here the simple form of the gauge illustrated in Fig. 34. It is made of glass as shown and is mounted on a vertical board. The difference in the heights of the mercury levels in the gauge and in the reservoir is approximately equal to the barometric pressure B. As the reservoir is raised, the mercury level in the gauge comes above the **Y**-branch, thus isolating a definite volume V_1 of the residual gas. This is isolated at the unknown pressure P_1, the pressure of the residual gas in the apparatus to which the gauge is connected. As the mercury reservoir is further raised, the isolated residual gas is compressed, and when its volume has been reduced to a volume V_2, the pressure is great enough to produce a sensible difference in the height of the mercury meniscus in the two capillaries, A and B. At the left, in Fig. 34, the mercury levels are shown at the beginning of a measurement, and at the right they are shown in two different positions corresponding to two methods of making readings. In one, if the meniscus in B is adjusted to the same height as the top of capillary A, the final volume, V_2, is equal to $\Delta h \cdot \sigma$, when σ is the cross-section area of the capillary. The decrease in volume from V_1 to V_2 is ordinarily of the order of one-hundred-thousandfold, with a corresponding increase of pressure in the capillary over that which obtained originally. The construction of the gauge with the comparison capillary B of identical bore with A eliminates the necessity of making corrections for surface tension. Referring to Eq. 1, we see that the product P_1V_1 is, in this case, a constant. The original product, P_1V_1, is equal to the final product, P_2V_2. From this we get the expression connecting the unknown pressure with the observed manometer difference, Δh:

$$P_1 = \frac{\sigma(\Delta h)^2}{V_1}. \tag{14}$$

V_1 and σ are constants of the gauge determined when it is constructed. σ is obtained by measuring the length of a known volume or weight of mercury in the capillary. V_1 is

determined by filling the gauge with mercury. These original data may be recorded on the board to which the gauge is attached. Here they will not be lost. Values of P_1 determined by Eq. 14 are usually laid off on a nonlinear scale, which is mounted behind capillary A in order that pressures may be read directly.

The second procedure of making the observations on V_2 and P_2 is illustrated at the right in Fig. 34. The gas is compressed to a definite mark on capillary A at a distance Δh_0 from the top, so that the final volume, V_2, is the same for every measurement. The final pressure necessary to compress volume V_1 to V_2 is Δh, and the pressure P_1 in the system is determined by these quantities, according to the following equation:

$$P_1 = \frac{\sigma \Delta h_0}{V_1} \Delta h. \tag{15}$$

A linear pressure scale computed from this formula is ordinarily mounted behind capillary B.

The McLeod gauge is thoroughly reliable for the permanent gases from 10^{-1} mm to 10^{-4} mm of mercury. It is less reliable to 10^{-5} mm. Below this the indications are only qualitative, and at 10^{-6} the mercury often sticks in the top of capillary A.

The gauge is most reliable after it has been outgassed by gently warming it with a soft flame. Three gauges with different values of V_1 are necessary to cover adequately the complete pressure range from 10^{-1} to 10^{-6} mm. Many of the designs of McLeod gauges are more elaborate than the one shown in Fig. 34. For example, three bulbs may be mounted together with one reservoir, one for low pressures, one for intermediate pressures, and one for high pressures.

The McLeod gauge is fragile. If it breaks, not only is the gauge lost but what is often more serious, mercury may get into the vacuum system. In glass vacuum systems using mercury pumps this is not as serious as it may be in kinetic vacuum systems. These systems, fabricated of brass with

soft-soldered joints, are attacked by mercury and the joints are destroyed.

Accidents with this gauge are usually caused by bringing the reservoir up too quickly. Then mercury in V_1 acquires enough momentum to shatter the bulb when the metal surface arrives at the opening of the capillary tube with no cushion of air to soften the shock.

Admitting air into the vacuum system is to be avoided when the mercury is not completely out of V_1. The admission of air will have the same result as carelessness in raising the reservoir.

Sometimes a mercury pellet will remain in capillary A when the reservoir is lowered. It can usually be brought down by tapping the capillary (after the mercury is all out of V_1). If this treatment fails, the capillary should be heated with a soft gas flame. In the latter case, a sheet of asbestos is placed behind the capillary to protect the calibration scale from the flame.

The capillary tubes used for the construction of McLeod gauges are seldom larger than 2 or 3 mm or smaller than $\frac{1}{2}$ mm bore. The volume of the bulb, V_1, ordinarily varies from 50 to 500 cc. Only pure distilled mercury should be used. Mercury is attacked by the sulphur present in rubber hose, so that dross is produced which adheres to the inside of the gauge and may become very annoying. A gauge contaminated with this sulphide may be cleaned out by the combined action of zinc dust and nitric acid. Rubber hose for use on a gauge should be cleaned before it is used by passing hot caustic potash solution back and forth through it for a quarter of an hour or so. The tubing should be thoroughly washed free of caustic and dried before use.

In cases where it is necessary to avoid contamination of the vacuum system with mercury vapor, a liquid air trap should be connected between the vacuum system and the gauge. For kinetic vacuum systems this precaution is often omitted. A stopcock between the gauge and the

system which is kept closed when the gauge is not in use minimizes contamination.

The ionization gauge.[46] Ionization gauges are triodes mounted in a glass bulb connected to the apparatus in which the pressure is to be measured. They are electrically connected as shown in Fig. 35.

Electrons emitted from the filament are accelerated to the grid, and their momentum would carry them to the plate if an inverse field more than sufficient to prevent this were not impressed between the grid and the plate. They therefore return to the grid and are finally collected on it. However, while they are between the grid and the plate, they bombard and ionize some of the molecules of the residual gas present there. These ions are collected on the plate and measured with a sensitive galvanometer. The ratio of this ion current to the current of bombarding electrons or grid current is proportional to the pressure at pressures below about 10^{-4} mm.

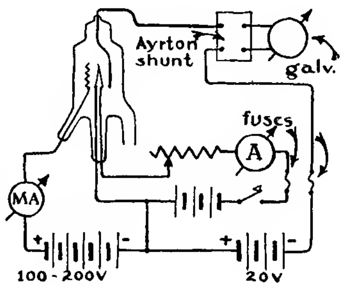

Fig. 35.

An ionization gauge may be made from an ordinary three-element radio tube equipped with a glass connection to the vacuum system. Such gauges are useful for the pressure range from 10^{-3} to 10^{-6} mm of mercury.

Fig. 36 shows the construction details of a gauge designed to have higher insulation of the plate than an ordinary radio tube. Measurements with it are possible to a pressure of 10^{-9} mm of mercury. The upper end of a glass bulb supports the plate assembly, while the lower end supports the combined grid and filament assembly. The grid is

[46] Buckley, O. E., *Nat. Acad. Sci., Proc.*, *2*, 683 (1916).
Dushman, S., and Found, C. G., *Phys. Rev.*, *17*, 7 (1921).
Jaycox, E. K., and Weinhart, H. W., *Rev. Sci. Instruments*, *2*, 401 (1931).
Simon, H., *Zeits. f. techn. Physik*, *5*, 221 (1924).

made from a piece of nickel screen rolled to form a cylinder. This is bound mechanically to the central glass tube through the bottom by wrapping it with wire, and it is connected electrically to the grid electrode with one loose end of the wrapping wire. There are two filaments, but only one is used. The other is held in reserve to be used if the first is accidentally burned out. The filaments may be replaced by cutting the central tube at S.

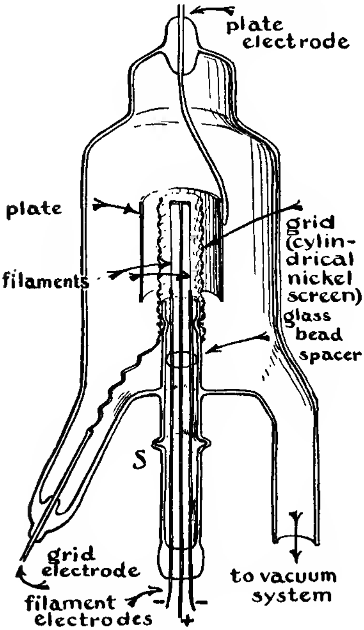

Fig. 36.

Expensive auxiliary electrical instruments are required for this gauge. They should be protected with Littlefuses as shown in the wiring diagram (Fig. 35).

The plate may be outgassed with high-frequency currents or by electron bombardment. In the latter case, an alternating potential of 500 volts is applied between the filaments and the plate. The amount of heat developed depends on the emission from the filament, and this is controlled by the filament current. Outgassing of the plate and glass walls of the gauge is necessary if quantitative measurements are to be made. However, for hunting leaks it is necessary only to outgas the plate once.

Dunnington has made a gauge using 30-mil helices of tungsten wire for both plate and grid. These helices are outgassed simply by passing a current through them for a few seconds. He found that such a gauge did not have a linear relationship between pressure and ratio of plate to grid currents. Once calibrated, however, it was found to be very reliable.

At a given pressure, the ratio of plate to grid current is different for different values of the grid current. For this reason, it is necessary to adjust the grid current to some definite value, usually in the range of 10 to 50 milliamperes.

The Pirani gauge.[47] The Pirani gauge consists of a heated filament of platinum, tungsten, or some other metal with a high temperature coefficient of electrical resistance. The filament is exposed to the residual gases and is cooled by them. The temperature of the filament is determined by the heat conductivity of the residual gas, which, in turn, depends on the pressure. The filament may be operated in several ways. The most satisfactory method is to connect the filament to one arm of a Wheatstone bridge and heat it by a constant current as shown in Fig. 37. If the bridge is balanced at one temperature of the filament, a change of its temperature caused by a change in the heat conductivity of the residual gases will unbalance it. Thus, the deflection of the bridge galvanometer indicates the pressure of the residual gases.

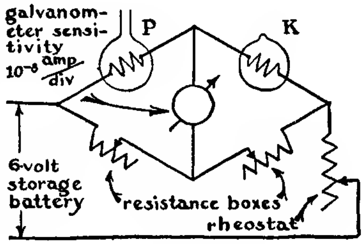

Fig. 37.

Ordinarily, the filament is mounted in a bulb fitted with a connecting tube and is balanced with an identical compensating filament mounted in an adjacent arm of the bridge. This auxiliary bulb is evacuated and sealed off at a very low pressure. The use of an auxiliary bulb serves to make the gauge insensitive to variations in room temperature. Changes in the over-all temperature of one bulb are the same as changes in the other, so that the galvanometer does not

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[47] DuMond, J. W. M., and Pickels, W. M., Jr., *Rev. Sci. Instruments*, *6*, 362 (1936).
Hale, C. F., *Am. Electrochem. Soc., Trans.*, *20*, 243 (1911).
von Pirani, M., *Deutsch. Phys. Gesell., Verh.*, *8*, 24 (1906).
Skellett, A. M., *J.O.S.A.*, *15*, 56 (1927).
Stanley, L. F., *Phys. Soc., Proc.*, *33*, 287 (1921).

respond to these changes but only to the changes produced by the residual gas in the one bulb.

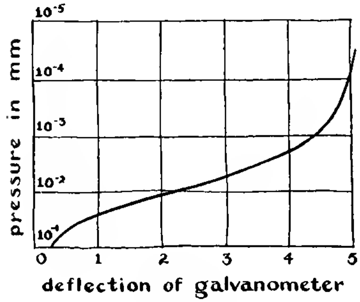

Fig. 38.

Fig. 38 shows a calibration curve of a Pirani gauge manufactured by E. Leybold Nachfolger. The pressure range over which it is useful extends from $\frac{1}{10}$ mm to 10^{-4} mm.

The construction of the Pirani gauge, together with the theory of its use, is treated in detail by several authors, who should be consulted by anyone planning to use the gauge for quantitative measurement. A gauge useful for qualitative work, as for hunting leaks, can be improvised from two ordinary 20- to 40-watt vacuum tungsten lamps, one of which is fitted with a connecting tube. Fig. 39 shows the construction details for this gauge. The bridge galvanometer should have a sensitivity of about 10^{-8} ampere division. Sometimes uncertain contact to the supporting wires may cause variable heat loss from the filament, and this should be suspected if the gauge is erratic. Tapping will often define the contact.

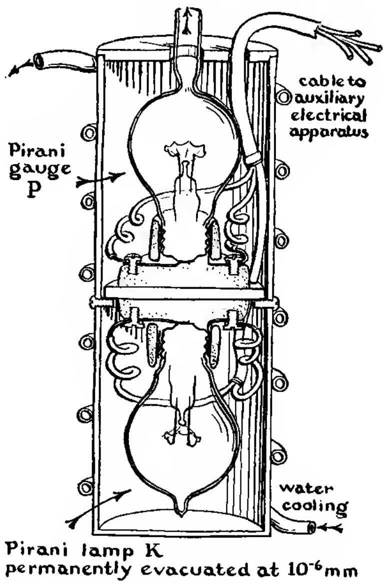

Fig. 39.

The Langmuir gauge.[48] Langmuir's viscosity gauge is

[48] Beckman, Arnold O., *J.O.S.A.*, *16*, 276 (1928).
Haber, F., and Kerschbaum, F., *Zeits. f. Elektrochem.*, *20*, 296 (1914).
Langmuir, I., *Am. Chem. Soc., J.*, *35*, 107 (1913).

made with a flattened quartz fiber about 50μ thick and from five to ten times as wide. This quartz ribbon is about 5 cm long and is mounted in one end of a glass tube about 25 mm in diameter, as shown in Fig. 40. When this ribbon is set vibrating in a high vacuum, the amplitude changes very slowly because the damping by the residual gas is almost negligible, and, owing to the low internal viscosity of fused quartz, the loss of vibrational energy from this source is also low. From atmospheric pressure down to a few millimeters of mercury, the damping produced by the molecules of the residual gas is nearly independent of pressure. Over the transition range of pressure, where the damping varies from this constant value to zero, the time required for the amplitude of vibration to decrease to half value is an index of the pressure. Within this range the relation between the time, t, the pressure, P, and the molecular weight of the residual gas is given by the following formula:

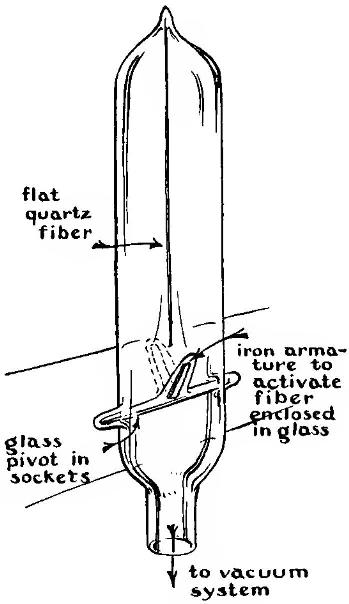

Fig. 40.

$$P\sqrt{M} = \frac{a}{t} - b. \tag{16}$$

Here a and b are constants of the gauge. The value of the ratio b/a may be obtained by observing the damping time, t_0, for an essentially perfect vacuum, that is, a pressure of 10^{-6} mm or less. For this pressure the left side of Eq. 16 can be set equal to zero. The values of a and b are determined from a second measurement of the time t_1 at a definite pressure P_1. This pressure is determined with a McLeod

gauge. *M* is approximately 29 for air. The gauge may also be calibrated by subjecting it to saturated mercury vapor at a definite temperature at which the vapor pressure of mercury is known. The range over which the gauge is most useful lies between the pressures 2×10^{-2} and 5×10^{-5}.

A feature of this gauge is its small volume. Because there are no metal parts exposed, the gauge is suitable for measuring the pressure of corrosive gases like the halogens. This gauge, in conjunction with a McLeod gauge, may be used for measuring the molecular weight of an unknown gas at low pressures.

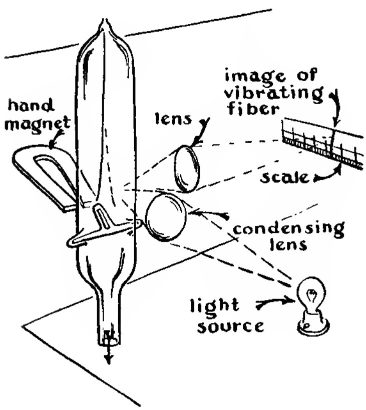

Fig. 41.

The flat quartz fibers may be obtained by drawing them out of the side rather than the end of a quartz tube or by following the technique given in Chapter V.

Figs. 40 and 41 show construction details and the method of mounting the fiber together with a pivoted glass tube, which contains an iron armature operated by an external electromagnet, to start the fiber vibrating. An optical arrangement for observing the amplitude of vibration is also shown. An image of the quartz fiber is projected on a scale with a simple lens.

The Knudsen gauge.[49] Fig. 42 shows the Knudsen gauge as designed by DuMond. When this gauge is constructed according to the specifications outlined by him, it is claimed to have a definite sensitivity, so that no preliminary McLeod calibration for it is needed. The gauge shown here differs slightly from DuMond's design in that it is equipped with a permanent (Alnico) magnet for damping.

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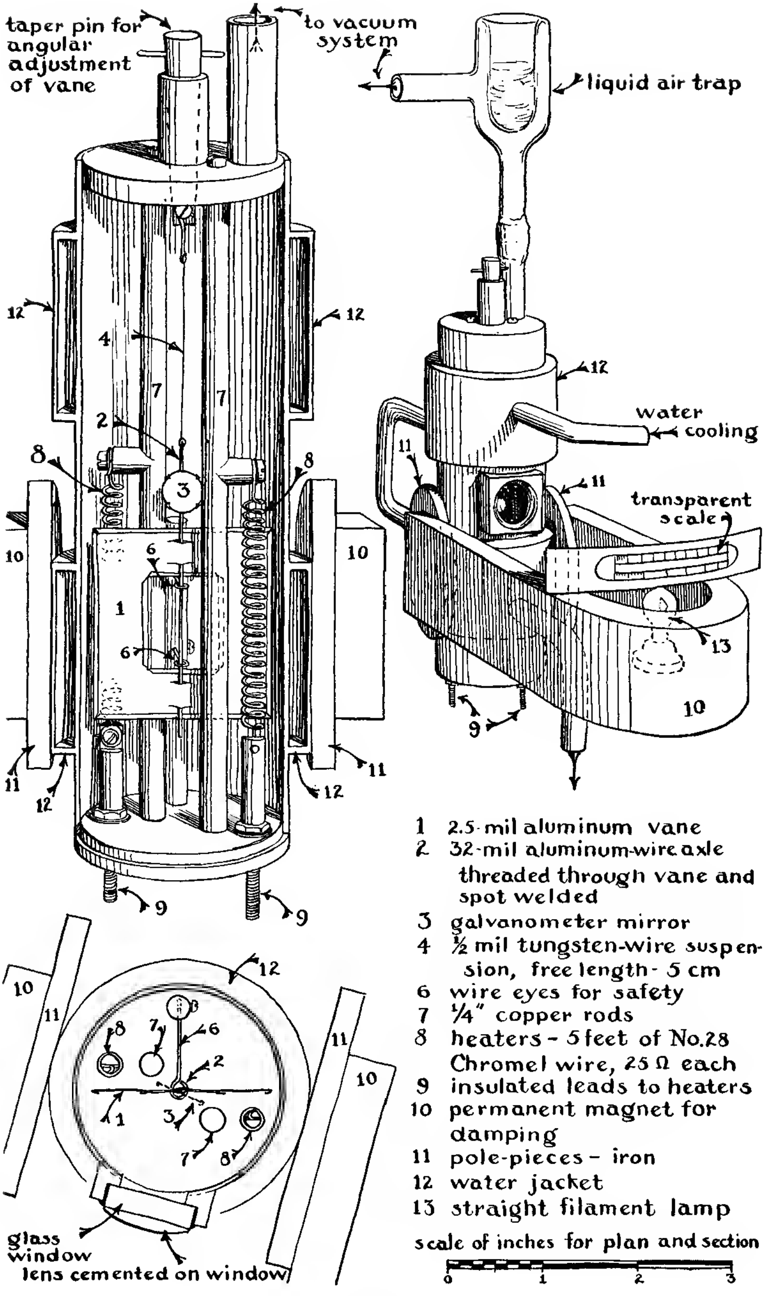
[49] DuMond, J. W. M., and Pickels, W. M., Jr., *Rev. Sci. Instruments*, *6*, 362 (1936).

Knudsen, M., *Ann. d. Physik*, *28*, 75 (1909).



taper pin for angular adjustment of vane
to vacuum system
liquid air trap
water cooling
transparent scale
1 2.5-mil aluminum vane
2 32-mil aluminum-wire axle threaded through vane and spot welded
3 galvanometer mirror
4 ½ mil tungsten-wire suspension, free length - 5 cm
6 wire eyes for safety
7 ¼" copper rods
8 heaters - 5 feet of No.28 Chromel wire, 25 Ω each
9 insulated leads to heaters
10 permanent magnet for damping
11 pole-pieces - iron
12 water jacket
13 straight filament lamp
scale of inches for plan and section
0
1
2
3
glass window
lens cemented on window

Fig. 42.

Also, it has a special liquid air trap for determining what fraction of the pressure indication is produced by condensable vapors.

The Knudsen gauge is to be preferred to the McLeod gauge where it is important to avoid contaminating a vacuum system with mercury. No expensive auxiliary instruments are required with the Knudsen gauge, as with the ionization gauge. Furthermore, the filaments will not burn out and the suspension is not delicate.

It is advisable to modify DuMond's design so that all connections and supports fasten to one end plate. This facilitates making repairs. The metal case thus becomes, in effect, a water-cooled covering "bell jar" fitted with a window.

CHAPTER IV

Coating of Surfaces: Evaporation and Sputtering

GLASS, quartz, and other nonmetallic substances may be coated in the laboratory with thin films of metal by the following processes:

1. Burning on
2. Chemical deposition
3. Cathode sputtering
4. Evaporation

Each of these is characterized by certain restrictions and advantages. For example, the "burning-on" method is applicable only in cases where the glass can be heated; chemical silvering (and also coating with gold and copper from aqueous solution) cannot be applied to surfaces like rock salt which are attacked by water; sputtering is particularly suitable for preparing films of the platinum metals; and the evaporation process is suited to the application of aluminum films.

Although deposits can be produced on metals as well as nonmetals by these processes, electroplating (not treated here) is usually the most practical for coating metals.

Burning-on method. Glass may be coated with a thin film of metal by the burning-on process. The process is applicable for the noble metals, which are reduced by heating. The glass to be coated is covered with a layer of an oily solution of one of the metallic salts. When heat is applied, the oil burns away, and the salt is reduced, leaving a deposit of the metal. This deposit is formed in an adherent

compact film by a final heating to the softening point of the glass.

A solution for depositing platinum[1] is made as follows: Evaporate 100 cc of a 10 per cent H_2PtCl_6 solution to dryness and dissolve it in a minimum quantity of absolute alcohol. Add this alcohol solution slowly to 6 cc of oil of lavender kept ice-cold. Finally, add some Burgundy pitch to give the mixture consistency, so that it will remain uniform when it is applied and the glass is slowly heated.

Solutions for gold, silver, and iridium are available commercially.

A platinum film burned onto porcelain may be electroplated with copper and soldered, thus affording a method of making a vacuum-tight seal between metal and porcelain.

Chemical silvering processes.[2] There are two widely used methods for chemical silvering. These are the Brashear method and the Rochelle salt method. The first is used to obtain thick coats on front-silvered mirrors which are to be frequently burnished, such as telescope mirrors. The Rochelle salt method, because its action is slower, is recommended for making partially silvered mirrors, such as interferometer plates, which require a uniform thin film with a specified ratio of reflection and transmission.

Cleaning. The silver film does not deposit well on contaminated surfaces. Therefore, fats and other surface contaminations must be cleaned off the glass, so that the colloidal particles of silver suspended in the silvering solution will adhere strongly to the glass to form a tenacious compact metallic film. Just as a greasy glass surface is difficult to wet with water, so a clean wet surface does not

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[1] McKelvy, E. C., and Taylor, C. S., "Glass to Metal Joints," *Amer. Chem. Soc., J.*, *42*, 1364 (1920).

[2] Gardner, I. C., and Case, F. A., "The Making of Mirrors by the Deposition of Metal on Glass," *Bureau of Standards Circular No. 389.*

Ingalls, Albert G., editor, *Amateur Telescope Making.* New York: Scientific American Publishing Company, 1935.

"The Making of Reflecting Surfaces," a discussion held by the Physical Society of London and the Optical Society, November 26, 1920. London: The Fleetway Press, Ltd.

readily take up greases, fats, and other contamination. Accordingly, once a surface is clean, it will stay clean, if it is kept under distilled water until it is immersed in the silvering solution.

The first step in cleaning a mirror is to free the sides and back of it from rouge and all other contaminations. An ink eraser is ideal for the removal of such contaminations. The pumice or ground glass in the eraser has an abrasive action particularly suitable for this preliminary cleaning of non-optical surfaces. The polished face cannot be cleaned in this manner, but it is well to work the eraser well over the edge.

The mirror is next washed all over with soap and water, or Aerosol[3] and water. Aerosol is preferred to soap, since it may be washed off the face of the mirror without leaving any residue. If soap is used, it should be rinsed off with rain water or, better yet, with distilled water.

A mild and harmless abrasive action on the face of a mirror is sometimes necessary. This is obtained by rubbing it with a pad of wet cotton, to which some precipitated chalk is added. After a polished glass surface has been treated with chalk, the cleaning water should wet the whole mirror face and not draw back anywhere to leave dry areas. It may be necessary to repeat the chalk treatment several times.

The mirror is next rinsed with water and swabbed with concentrated nitric acid, a powerful oxidizing agent which removes organic matter adsorbed on the glass. The swab for applying the acid is made by wrapping absorbent cotton

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[3] The compound Aerosol OT is manufactured by the Selden Division of the American Cyanamid and Chemical Corporation, Bridgeville (Pittsburgh), Pennsylvania.

Duncan, R. A., *Indust. and Engin. Chem.*, *26*, 24 (1934). This article gives a description of new detergents of which Aerosol is an example. These detergents have in common the constitution of sulphonated organic compounds of high molecular weight. They have a neutral reaction, and their advantage over soap for washing mirrors lies in the fact that they may be used in neutral, caustic, or even acid solutions. Unlike soap, they form soluble compounds with magnesium and calcium ions, which are common in tap water. The detergent Dreft, obtainable at grocery stores, is also suitable for washing mirrors.

on a glass rod and fastening it with cotton twine as shown in Fig. 1. Care is exercised in using the swab to prevent the end of the rod from coming in contact with the mirror face. This nitric acid treatment should be carried out in the container in which the mirror is to be silvered to avoid possible contamination later with oil from the hands when the mirror is handled. If it is necessary to handle the mirror, it is advisable to use rubber gloves.

Cleaning solution (chromic and sulphuric acid mixture) may be used for cleaning glass, but it is not ordinarily necessary. This solvent is very effective. Even paraffin and carbonized organic material may be removed from glass in cases where the glass and the chromic acid solution can be heated together.

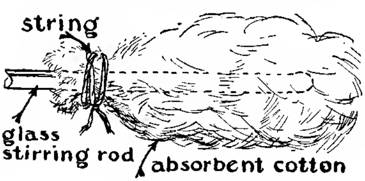

Fig. 1.

After being rinsed with tap water, the mirror is treated with a concentrated solution of stannous chloride. This is removed after a few minutes by a very thorough rinsing. All chloride ions must be washed away, first with tap water and finally with distilled water. The mirror can stand in the distilled water until the silvering begins.

It is important in silvering to clean carefully all the receptacles and graduates used. A long stick with an ink eraser fastened to the end will be found helpful to remove water stains and other contaminations.

Brashear's process.[4] The Brashear process is described graphically in Fig. 2. The three formulas for the reducing solution given there afford different ways to effect the same end. In the first formula the nitric acid slowly digests the table sugar, to yield the sugars dextrose and levulose. This requires time and so the solution must be aged before use. In the second formula this aging is accelerated by boiling, and the solution can be used as soon as it is cool.

[4] Brashear, John A., *English Mechanic*, *31*, 237 (1880).
Wadsworth, F. L. O., *Astrophys. J.*, *1*, 352 (1895).

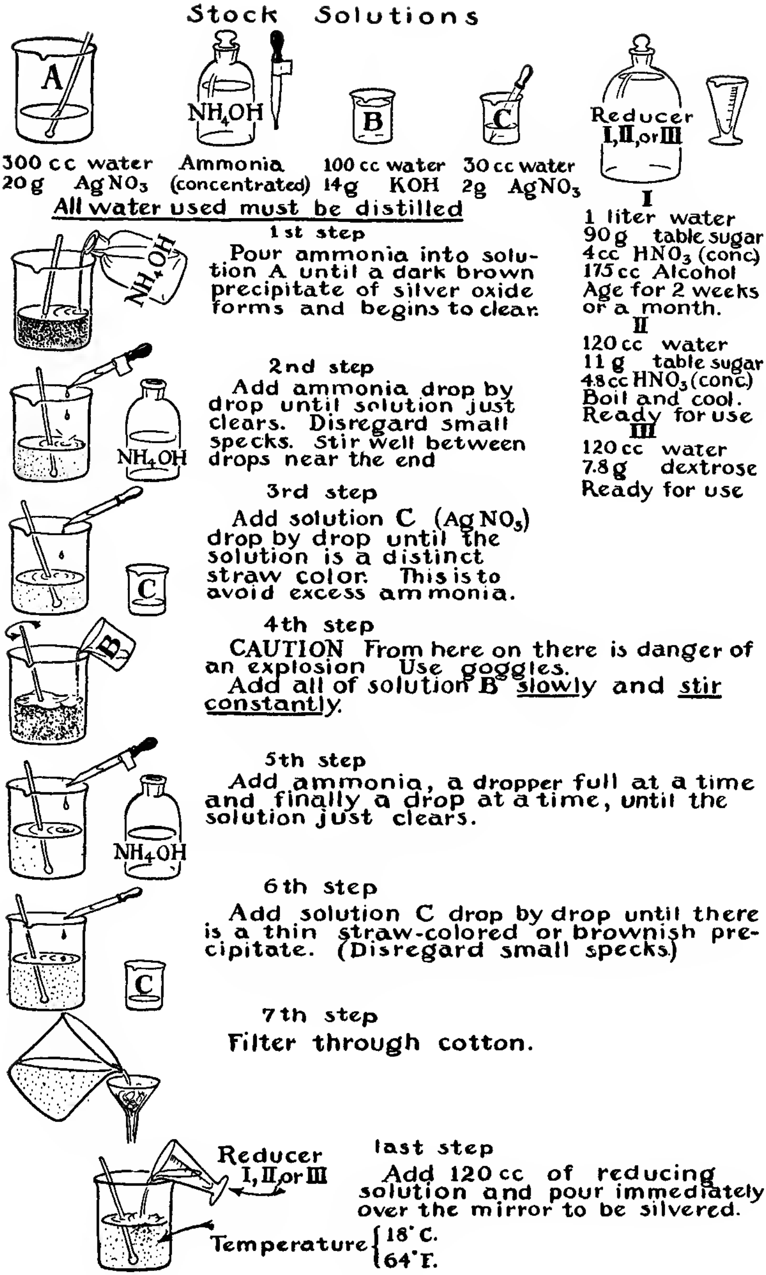
Stock Solutions
A
NH₄OH
B
C
Reducer I, II, or III
300 cc water 20 g AgNO₃
Ammonia (concentrated)
100 cc water 14 g KOH
30 cc water 2 g AgNO₃
All water used must be distilled
I
1 liter water
90 g table sugar
4 cc HNO₃ (conc)
175 cc Alcohol
Age for 2 weeks or a month.
II
120 cc water
11 g table sugar
4.8 cc HNO₃ (conc.)
Boil and cool.
Ready for use
III
120 cc water
7.8 g dextrose
Ready for use
1st step
Pour ammonia into solution A until a dark brown precipitate of silver oxide forms and begins to clear.
NH₄OH
2nd step
Add ammonia drop by drop until solution just clears. Disregard small specks. Stir well between drops near the end
NH₄OH
3rd step
Add solution C (AgNO₃) drop by drop until the solution is a distinct straw color. This is to avoid excess ammonia.
C
4th step
CAUTION From here on there is danger of an explosion Use goggles.
Add all of solution B slowly and stir constantly.
B
5th step
Add ammonia, a dropper full at a time and finally a drop at a time, until the solution just clears.
NH₄OH
6th step
Add solution C drop by drop until there is a thin straw-colored or brownish precipitate. (Disregard small specks.)
C
7th step
Filter through cotton.
Reducer I, II or III
last step
Add 120 cc of reducing solution and pour immediately over the mirror to be silvered.
Temperature 18° C. 64° F.

Fig. 2.

In the third formula dextrose is used directly. The alcohol is a preservative, and it is not required for the second and third solutions unless they are to be stored, in which case the same proportion of alcohol is used as called for in the first formula.

There is danger of an explosion after the fourth stage, indicated in Fig. 2. The formation of the explosive, fulminating silver, is not particularly favored by the low concentration of solutions and moderate temperatures that obtain here, but these relatively weak solutions will give fulminate on warm days if they are allowed to stand. This compound explodes on the slightest provocation when dry and sometimes when wet. Accordingly, all spent silver solutions should be rinsed down the sink at once. Goggles are recommended for safety.

As soon as the reducing reagent is added, the silvering solution is poured over the mirror. Filtering is optional. The distilled water in which the mirror has been standing may or may not be poured off first. Soon after the reducer is added, the solution becomes dark brown and then black. After this, it gradually develops a muddy brown appearance. At this stage the deposit of silver on the mirror is already continuous or should soon become so. The container for the mirror and solution may be tipped from time to time to stir the solution and allow inspection of the surface. When the silver film covers the whole surface and as soon as black specks begin to settle on it, a light swabbing with a cotton pad is recommended. This rubbing must be delicate at first, but it may be more vigorous as the silver becomes thicker, the surface being inspected from time to time for bloom. Usually when the solution begins to clear, it is nearly spent, and since the possibility of bloom becomes greater at this stage, it is best to pour off the solution and rinse the mirror with distilled water. For a full silver coat, Brashear's process requires, on the average, from 6 to 10 minutes.

If a bright light, such as the sun, is visible through the coat, it is too thin. In this case the mirror should be covered

with distilled water, and the chemical solution for a second coat prepared. Do not let the mirror dry between coats.

After a satisfactory coat is obtained, the rinsed mirror is rubbed with a pad of cotton until it is dry. The silver is burnished with a burnishing pad (chamois skin tacked on a Shinola shoe-polishing pad) to "compact" the coat. It is then polished with a similar chamois pad charged with optical rouge. The rouge pad may also be used from time to time to burnish away tarnish which forms on the silver mirror.

Rochelle salt process.[5] Two solutions are required for the Rochelle salt process. Solution *A* is made as follows: 5 g of silver nitrate are dissolved in 300 cc of water and ammoniated, as in the Brashear process, so that the silver oxide precipitate formed at first is almost but not completely clear. In case it inadvertently becomes clear, it must be back-titrated with a dilute solution of silver nitrate, so that the liquid finally presents a distinct straw color. This is filtered and diluted with water to 500 cc. Solution *B* is made as follows: 1 g of silver nitrate is dissolved in 500 cc of water. It is then brought to a boil, and 0.83 g of Rochelle salt, dissolved in a little water, is added. The boiling is continued until a gray precipitate is deposited. The solution is filtered hot and diluted to 500 cc. These solutions may be stored for a month or so if they are protected from light.

To silver a mirror, solutions *A* and *B* are mixed, volume for volume, and poured at once into the silvering vessel. The quantity of solutions given above is sufficient for a thick film on a glass surface of 200 cm^2 area. The temperature recommended for silvering is 20°C. (68°F.).

Silver is deposited slowly by the Rochelle salt process; an hour may be required for a thick deposit to form. Partial reflecting films are obtained as desired by withdrawing the glass from the solution at the appropriate time. The progress of the deposition may be judged from auxiliary

[5] This treatment follows that given in Miller, Dayton Clarence, *Laboratory Physics*, page 269. Boston: Ginn and Company, 1903.

glass plates, which are removed from time to time to determine the progress of the coating on the main plates. Fig. 3 illustrates a simple test for determining when the silver film is half-reflecting (for 45° incidence).

Partial reflecting plates are washed with distilled water and dried. Afterward they are polished by a light brushing with an eiderdown powder puff charged with optical rouge, as recommended by Pfund.

Silver films are protected from tarnishing by covers of filter paper that have been soaked with lead acetate solution

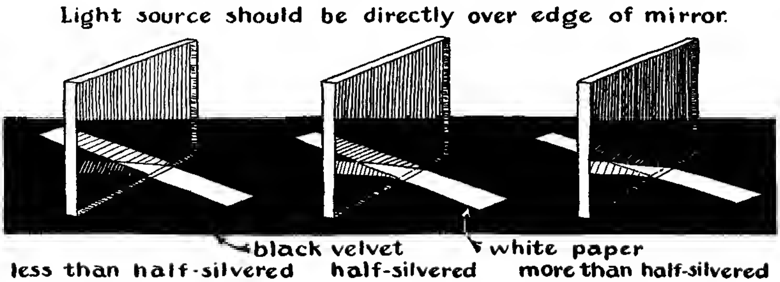

Fig. 3.

and dried. These covers are applied whenever the films are not actually in use.

Lacquering. Another procedure for protecting the silver from tarnishing involves coating the film with a thin layer of colorless lacquer. The layer of lacquer destroys some of the reflectivity of the mirror, and in addition it exhibits interference colors. R. W. Wood has pointed out that a thin transparent film of lacquer on a good reflector should not show interference colors.[6] The colors usually exhibited by a lacquer film are due to frilling. This frilling can be observed directly only with the highest-power microscopes. Wood states that no frilling occurs and that there are, accordingly, no interference colors if collodion dissolved in chemically pure redistilled ether is used to lacquer the mirror.

[6] Wood, Robert W., *Physical Optics*, Third Edition. New York: The Macmillan Company, 1934.

In order to obtain uniform lacquer films with the ether solution of collodion, it is necessary that the ether evaporate slowly. The can illustrated in Fig. 4 is suggested for use in lacquering with an ether solution.

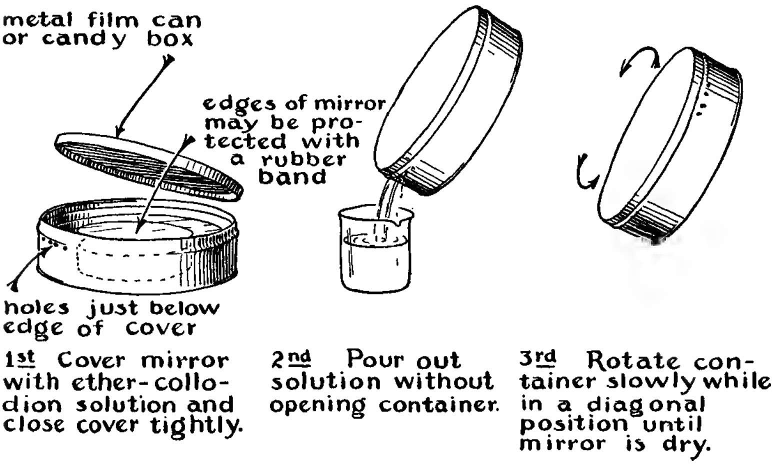

Fig. 4.

Gold and copper. A chemical process for depositing gold from solution is described by von Angerer.[7] A process for copper is described by French.[8]

Sputtering. Although the sputtering phenomenon at the cathode of a glow discharge has been known for a long time,[9] the mechanism of the process is not fully understood even now.[10] There are two current theories of sputtering. One of these holds that the emission of metal by the cathode is pure thermal evaporation due to high temperatures attained in areas of molecular dimensions. These tempera-

[7] von Angerer, Ernst, Wien-Harms, *Handb. der Exp. Physik, 1,* 375 (1926).

[8] French, E. A. H., *Optical Soc., Trans., 25,* 229 (1924).

[9] Grove discovered the sputtering phenomenon in 1852. Grove, W. R., *Phil. Trans., 1* (1852).

[10] Compton, Karl T., and Langmuir, Irving, *Rev. Modern Physics, 2,* 186 (1930).

Fruth, H. F., *Physics, 2,* 286 (1932), gives a comprehensive bibliography of cathode sputtering.

Mierdel, G., Wien-Harms, *Handb. der Exp. Physik, 13,* Part 3, page 400 et seq. (1929).

tures are produced by the energy of impinging ions. The other theory invokes a mechanism for transferring the energy of the gas ion into energy of a metal molecule which is similar to the mechanism by which the energy of a light quantum is transformed to energy of an emitted electron. However, in spite of its being incompletely explained, sputtering is understood empirically, and its practical application for obtaining metal films on glass is simple.

Sputtering can be carried out successfully under a wide variety of conditions. For example, the pressure of the glow discharge may range from 1 down to 10^{-2} mm. The cathode is naturally made of the metal to be sputtered, although its shape may vary considerably. The anode is usually aluminum or iron. The glow discharge is preferably produced by a direct potential, although an alternating potential can be used. The potential usually ranges above 1000 volts and frequently is as high as 20,000 volts. The residual gas in the sputtering chamber may be air, hydrogen, argon, or other gases. (The sputtering rate with helium is extremely low, and this gas is used for glow discharges where sputtering is to be avoided.) The surface to be sputtered is usually placed tangent to the boundary of the cathode dark space, although it may lie within or beyond it. The low pressure required can be obtained with a mechanical pump of small capacity on a tight system or with a faster mechanical or diffusion pump on a system equipped with a regulating leak.

A typical setup for the sputtering process is shown in Fig. 5. The sputtering chamber is usually a glass bell jar with a hole in the top for the cathode connection. It may be made from an old bottle with the bottom cut out and the base ground flat. It is best to have a glass plate for the base, although a metal one (preferably iron) will suffice. An aluminum plate can be used to cover any exposed metal parts which may give trouble by sputtering. It is advisable to heat all aluminum before it is used in order to drive off the machine oils which may be contained in it. Glass cylinders

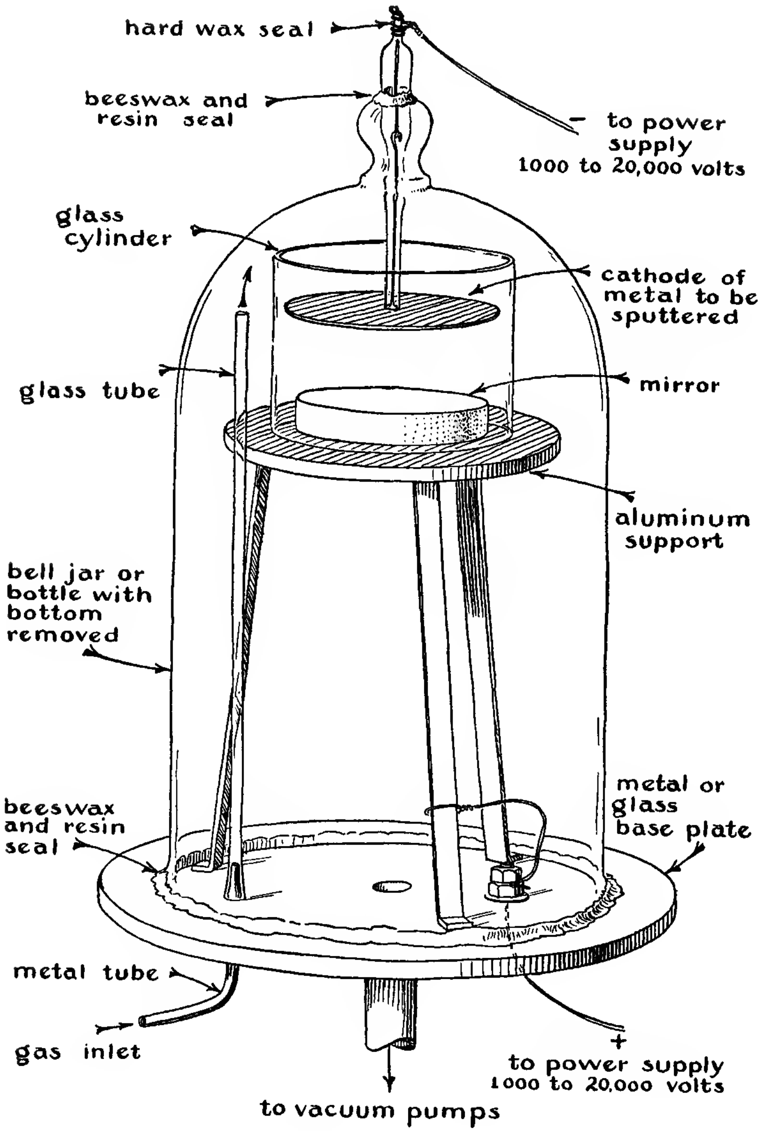
hard wax seal
beeswax and resin seal
- to power supply 1000 to 20,000 volts
glass cylinder
cathode of metal to be sputtered
glass tube
mirror
aluminum support
bell jar or bottle with bottom removed
metal or glass base plate
beeswax and resin seal
metal tube
gas inlet
+ to power supply 1000 to 20,000 volts
to vacuum pumps

Fig. 5.

and plates, as shown in Fig. 5, are useful for confining the discharge. If these plates and cylinders are not used, the outgassing induced by the discharge may give rise to foreign substances deleterious to the film produced.

The cathode is fitted in the top of the bell jar as shown. It is pulled up against the square end of the depending glass tube by the connector wire. This wire is secured by wrapping it around the top end of the tube, where it is sealed with wax (Apiezon "W," shellac, or DeKhotinsky wax).

Batteries or motor-generator sets are ideal sources for the sputtering potential, but other sources of potential are often employed. An induction coil makes a convenient source of potential, giving partially rectified current. However, alternating current from a 10,000-volt neon-sign transformer can be used. It is advisable but not necessary to rectify the current from this transformer with a Kenetron rectifier.

The use of a milliammeter to measure the discharge current is advisable when making partially transmitting coats. When the sputtering equipment has been calibrated, this current serves as an index to determine proper exposure for obtaining a desired ratio of transmission and reflection. The sputtering rate can be controlled, for example, by adjusting the filament current of the Kenetron. The rate of sputtering increases a little more than linearly with the sputtering current, depending somewhat upon the conditions of temperature, pressure, and geometry which obtain. For work in which high reproducibility in the film thickness is required, it is advisable to use a fast pump and to wash the bell jar continuously with air or hydrogen. Inasmuch as the first part of the sputtering may be erratic and the discharge unsteady, it is well to cover the mirror with mica until sputtering has definitely started and become stable. This mica is mounted on pivots with an attached iron armature, so that it can be operated with the help of a magnet through the walls of the bell jar; or it may be operated by tipping the whole system.

The pressure for sputtering is usually adjusted so as to give a dark space of about the same length as the distance of the mirror from the cathode.

The cathode should be shaped so that the boundary of the dark space is roughly parallel to the mirror surface. For flat or nearly flat mirrors the cathode is made flat, while for strongly curved mirrors it should be correspondingly curved. A **U**-shaped sheet cathode can be used for coating the two sides of a plate at once, and a central wire cathode can be used to coat the inside of tubes, provided that their length is not much greater than their diameter. Conversely, a cylindrical cathode can be used for coating fibers on all sides at once and for coating the outside of tubes.

The gas admitted, when fast pumps are used, may be air, hydrogen, or argon. Hydrogen is preferred by some even

TABLE I

SPUTTERING RATES OF METALS

Observer	Gas	Rate of Sputtering in Descending Order
Crookes..........	air	Pd, Au, Ag, Pb, Sn, Pt, Cu, Cd, Ni, Ir, Fc, Al, Mg.
Kohlschütter......	N_2	Ag, Au, Pt, Pd, Cu, Ni.
Blechschmidt......	A	Cd, Ag, Pb, Au, Sb, Sn, Bi, Cu, Pt, Ni, Fe, W, Zn, Si, Al, Mg.
Güntherschulze....	H_2[a]	Bi 1470, Tc 1200, As 1100, Tl 1080, Sb 890, Ag 740, Au 460, Pb 400, Zn 340, Cu 300, C 262, Sn 196, Fe 68, Ni 65, W 57, Co 56, Mo 56, Mn 38, Cd 32, Al 29, Cr 27, Ta 16, Mg 9.
Güntherschulze.....	O_2[a]	Zn 1030, Tl 650, Ag 614, Au 423, Pb 320, Cu 236, Sn 227, Fe 86, Mo 80, W 49, Ni 52, Cd 28.

Crookes, Sir W., *Roy. Soc., Proc.*, *50*, 88 (1891).

Kohlschütter, V., *Zeits. f. Elektrochem.*, *15*, 316 (1909); *Jahrb. Radioaktivitat*, *9*, 335 (1912).

Güntherschulze, A., *Zeits. f. Physik*, *36*, 563 (1926), *38*, 575 (1926).

[a] Numbers give rate of sputtering in milligrams per ampere hour under conditions of cathode fall of 770 volts and current density of about 7 milliamperes/cm^2.

though it has a very slow sputtering rate. The hydrogen may be obtained from a tank or from a gas electrolysis chamber. The relative sputtering rates for the various metals with different residual gases are given in Table I and Fig. 6.

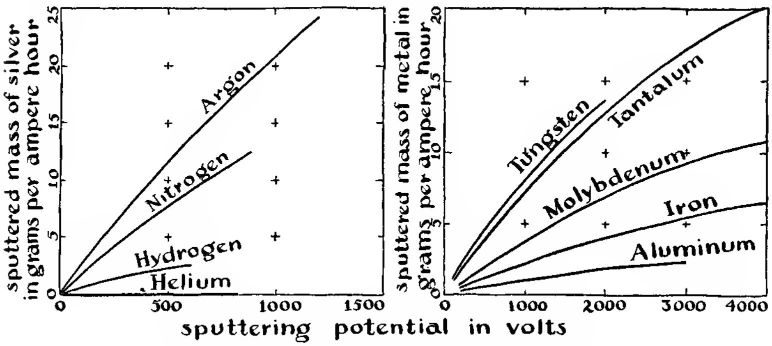

Fig. 6. Güntherschulze's measurements of sputtering rates.

E. O. Hulburt [11] has recently made a study of sputtering. He determined the rates of sputtering in a residual atmosphere of air at a pressure giving 5 cm dark space. The voltage he used was 1000 to 3000 volts and the current 50 milliamperes. The cathode was 5 cm in diameter and 2 to 4 cm from the surface coated. His results are given in Table II.

TABLE II

TIME TO OBTAIN METAL FILMS BY SPUTTERING

Metals	Time
Sb, Bi, Cd, Au, Pb, Pt, Ag, Sn, Zn	Opaque coating in 1 hour
Co, Cu, Ir, Fe, Ni, Se, Te	Opaque coating in 2 hours
Mo, Ta, W	Opaque coating in several hours
Al, Be, C, Cr, Mg, Si	Extremely low sputtering rate

Hulburt states that the use of mercury vapor enormously increases the sputtering rate of chromium, aluminum, and

[11] Hulburt, E. O., *Rev. Sci. Instruments*, *5*, 85 (1934).

silicon. Optical films of these metals were produced in less than 15 hours in this vapor. Good but not entirely opaque optical films of beryllium were obtained after sputtering for 60 hours in hydrogen and mercury vapor.

Clean dry surfaces and breath figures. To get a surface both clean and dry as required for sputtering and evaporation is a great deal more difficult than to clean it for chemical silvering as described above. Most surfaces cleaned and then dried with absorbent cotton or a towel are found to condense the breath in a gray film. The reason is that in the drying process the glass surface becomes coated with a layer of contamination, which is probably a monomolecular film of fatty acid gathered from the cotton. Water condenses on such a film in tiny droplets, while on a really clean surface it condenses in an invisible uniform film.

Surfaces can be chemically cleaned and dried in a desiccator. Such surfaces give a continuous deposit when breathed on. Also, surfaces may be dried with linen without contaminating them, as Wm. B. Hardy has succeeded in doing. Hardy found it necessary, however, to use linen from which the oily compounds had been extracted with pure benzene.

However, a method to remove the contamination picked up from the towel when the mirror is dried is more practical than to depend upon successfully avoiding such contamination. This dry cleaning can be effected by the action of ions.

The study of this action of ions on the surface of glass started with Aitken and Lord Rayleigh.[12] They found that when the tip of a blowpipe flame was passed quickly over the surface of the glass, it cleaned the surface and produced a so-called breath figure; that is, if one breathed on the glass, the moisture condensed in a gray film of fine droplets, except that where the flame had traversed the surface, the moisture condensed in the form of a continuous "black" film. T. J. Baker and others have carried the study of breath figures

[12] Lord Rayleigh, *Scientific Papers*, Vol. 6, pages 26 and 127. Cambridge: University Press, 1920. Aitken, *Roy. Soc. Edin., Proc.*, *94* (1893).

further.[13] For example, Baker found that they were produced only by the hotter flames, which are rich in ions. Among the interesting phenomena revealed by his investigation was that breath figures could also be produced by sparks, and that, curiously, they could be transferred from one glass plate to another if the two plates were held together but not quite in contact. He also discovered that the black area is a relatively good conductor of electricity and that the coefficient of friction between glass and glass was very high in the black area. Fig. 7 illustrates a simple experiment for demonstrating this difference in friction between glass which has been flamed and that which has not been flamed.

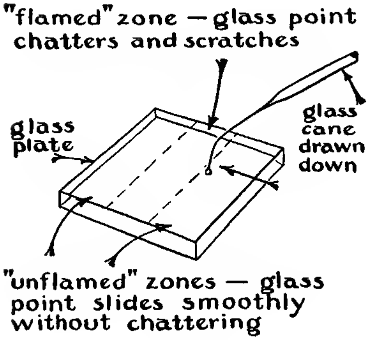

Fig. 7.

A. C. F. Pollard[14] found it easy to obtain good adherent films of chemical silver on glass by passing a blowpipe over the surface of the glass before immersion in the silvering solution. He also found that for a short time a freshly fractured glass surface condenses moisture in a continuous black film.

As a parallel to Pollard's discovery, it was found that aluminum coats prepared by evaporation in vacuum adhere so tenaciously to areas that have been flamed that they cannot be removed by stripping Scotch tape off the film, although the tape removes the aluminum from regions not traversed by the flame.[15] Also, the black type of condensation, as well as good adhesion of an aluminum film, occurs after a glass surface is exposed to sparks at atmospheric pressure or to a glow discharge at reduced pressure. The explanation

[13] Baker, T. J., *Phil. Mag.*, *44*, 752 (1922).

[14] "The Making of Reflecting Surfaces," a discussion held by the Physical Society of London and the Optical Society, November 26, 1920.

[15] Strong, J., *Rev. Sci. Instruments*, *6*, 97 (1935).

of all these phenomena is that the ions of the hotter flames, sparks, or glow discharges clean the surface of the glass.

The practices adopted to effect a final cleaning of a glass surface are either to expose it to the brush discharge from the electrode of a high-frequency transformer at atmospheric pressure or to expose the glass to a glow discharge in an evaporation chamber while it is being evacuated.

Cleaning mirrors for aluminizing. When aluminum is deposited on a glass surface which is not adequately cleaned, the adhesion will be inferior to that exhibited by a coat on a properly cleaned surface. In most cases the mirror will look good at first but will develop countless tiny blisters after standing a day or so.

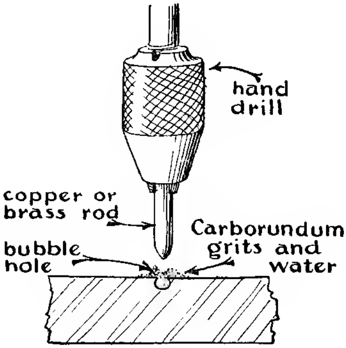

Fig. 8.

The first phases of the cleaning procedure for aluminizing are like those for chemical silvering. The preliminary cleaning with the rubber eraser is carried out with particular thoroughness. Small bubble holes in the face of the mirror that contain rouge and pitch from the figuring should be ground out with emery as shown in Fig. 8. If the rouge and pitch in small bubble holes is not removed, the towel used for drying the mirror may pick up some of the pitch and spread it over the surface of the mirror face in layers too thick to be removed by electrical cleaning.

After the glass has been cleaned and rinsed as described above for silvering, it is dried with clean cotton towels. It is well to use old cotton towels, because after many launderings they become more absorbent and contain less fatty substances than absorbent cotton. Care is exercised to avoid contaminating the freshly laundered towel by touching it with the hands in the areas to be used to dry the mirror face.

Finally, the glass is exposed to a glow discharge during the evacuation.

Evaporation. The evaporation method for producing thin films on glass, quartz, and so forth, is simple both in its mechanism and in its practical application. A small piece of the metal (or nonmetal, for that matter) is simply heated in a high vacuum until its vapor pressure is about 10^{-2} mm of mercury or greater, whereupon it emits molecular rays in all directions. The degree of vacuum required for successfully carrying out the process is such that the mean free path of the molecules is larger than the diameter of the vacuum container. Therefore molecular rays propagate from their source without disturbance until they impinge on the walls of the vacuum or some object within them. The mirror surface to be coated is exposed to these molecular rays, which condense on it to form the desired film. An interesting feature of the condensed film is that it apparently exhibits the same degree of polish as the underlying glass and so requires no subsequent burnishing, as does chemical silvering. Also, this film forms without material heating of the mirror.

Although the evaporation method was known by 1912, it remained obscure, for some reason, long after it should have become a practical "tool" in the laboratory.[16] Among the items which have influenced its recent rather extensive applications are the development of a bare tungsten heater technique,[17] the adaptability of the process to nonmetals and for the application of aluminum,[18] and the development of high-speed vacuum pumps. (See Chapter III.)

Whether or not a particular material is suited to giving films by the evaporation process is determined by the thermal stability and vapor pressure of the material and the practicality of bringing the material to the evaporation temperature in vacuum.

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[16] Pringsheim, P., and Pohl, R., *Deutsch. Phys. Gesell., Verh., 14*, 506 (1912).
[17] Ritschl, R., *Zeits. f. Physik, 69*, 578 (1931).
[18] Strong, J., *Astrophys. J., 83*, 401 (1936).

Tungsten heaters useful for bringing some of the metals to the evaporation temperature are shown in Figs. 12 and 15 to 20. The evaporation temperatures of the metals are given in Table III.

TABLE III

EVAPORATION TEMPERATURE OF DIFFERENT METALS

Material	Evaporation Temperature $T°$ Absolute[a]	Material	Evaporation Temperature $T°$ Absolute[a]
Hg	320	Pb	1000
Cs	433	Sn	1148
Rb	450	Cr	1190
K	480	Ag	1319
Cd	541	Au	1445
Na	565	Al	1461
Zn	623	Cu	1542
Mg	712	Fe	1694
Sr	811	Ni	1717
Li	821	Pt	2332
Ca	878	Mo	2755
Ba	905	C	2795
Bi	913	W	3505
Sb	973		

[a] Temperature at which vapor pressure = 10^{-2} mm of mercury.

Baur, E., and Brunner, R., *Helv. chim. Acta.*, *17*, 959 (1934).
Espe, W., and Knoll, M., *Werkstoffkunde der Hochvakuumtechnik*, page 358. Berlin: Julius Springer, 1936.
Knoll, M., Ollendorff, F., and Rompe, E., *Gasentladungs-Tabellen.* Berlin: Julius Springer, 1935.
Landolt-Börnstein, *Phys. Chem. Tabellen*, Fifth Edition. Berlin: Julius Springer, 1923–1936.
Leitgebel, W., *Metallwirtschaft*, *14*, 267 (1935).

Most of the metals melt first before they evaporate, the molten metal being kept from falling out of the coil by surface tension.

Other metals, like magnesium, sublime. Of these, some sublime very slowly, because the metal will not fuse to the tungsten wire in vacuum. Chromium affords an example. The evaporation of such a metal is managed as follows: It is first brought to fusion temperature in the tungsten coil in an atmosphere of hydrogen or helium. These gases

facilitate heat transfer between tungsten and the chromium or other metal, and, in addition, they restrain evaporation of the metal. (See Fig. 9.) After intimate contact with the tungsten wire is established, the metal will then sublime

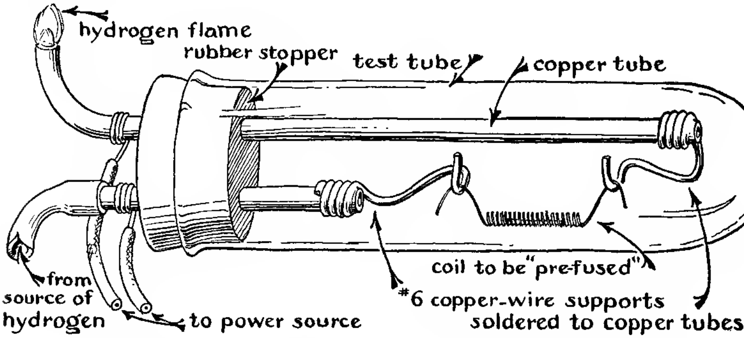

Fig. 9. Arrangement for pre-fusion of metal to tungsten coil.

faster in the vacuum, because the heat is transmitted to it more effectively. An alternate way of attaining the same end is to electroplate the chromium or other metal onto the tungsten coil.[19] The metals best managed by the above procedures include, besides chromium, the platinum metals and beryllium.

Frequently, it is desirable to prefuse a metal which otherwise sublimes, in order to free it from included impurities. Such metals as calcium, magnesium, and cadmium can be prefused in helium to outgas them and to prepare them for evaporation.

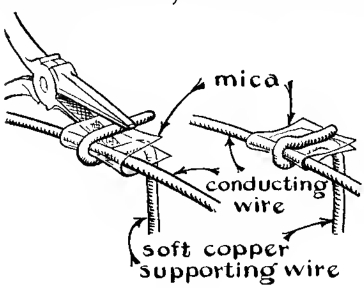

Fig. 10.

A great many metals react with the tungsten coil, as, for example, iron, nickel, beryllium, chromium, the platinum

[19] This electroplating technique is apparently one which has been frequently used. Note the following references on its application to platinum and chromium respectively:

Strong, J., *Phys. Rev.*, *39*, 1012 (1932).

Williams, Robley C., *Phys. Rev.*, *41*, 255 (1932).

metals, and aluminum. In spite of this, it is possible to evaporate them for the preparation of small laboratory mirrors.

Fig. 10 shows a neat simple insulated support for wires in vacuum.

Evaporation technique for aluminum. The technique for evaporation of aluminum from tungsten coils is of special interest, since this metal is important for surfacing where high ultraviolet and high visible reflectivity are desired in combination with freedom from tarnishing.

Pringsheim and Pohl discovered that several metals (including aluminum) could be evaporated in vacuum and condensed on a glass surface to form a polished reflecting film. They used a magnesia crucible from which to distill the metal.[20] R. Ritschl, in 1928, in making an application of the evaporation method to the preparation of half-silvered interferometer mirrors, heated the silver in a bare tungsten coil.[21] This change in technique has the advantage that the tungsten does not evaporate or outgas so much in a vacuum as does the magnesia crucible.

Following this, Cartwright and Strong developed a simple apparatus for carrying out the evaporation process in the laboratory and made a survey of its applicability to different metals.[22] The usual technique, in which the metal to be evaporated was heated in a helix of tungsten wire, was found successful, except with the metals aluminum and beryllium, which dissolved the tungsten coil.

Other attempts were made to develop this technique of evaporating aluminum.[23] Experiments were carried out with crucibles of graphite, pure fused magnesia, and alumina (sapphire), as well as with sintered and fused crucibles of thorium oxide. These experiments showed that heating in a crucible was apparently impractical, since either the metal

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[20] See footnote 16.

[21] See footnote 17.

[22] Cartwright, C. Hawley, and Strong, J., *Rev. Sci. Instruments*, *2*, *189* (1931).

[23] Cartwright, C. Hawley, *Rev. Sci. Instruments*, *3*, 302 (1932).

reacted chemically with the material of the crucible or the latter evaporated when the aluminum was heated.

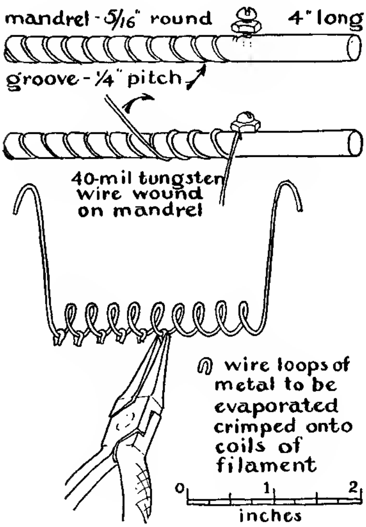


Fig. 11.

The discovery that tungsten has a limited solubility in molten aluminum led to the bare tungsten method of evaporation—the most practiced of all the methods.[24]

A chemical analysis of the tungsten alloy that is formed when aluminum is fused on a tungsten coil showed the solubility of tungsten in aluminum to be about 3 per cent by volume. Accordingly, the burning out of the tungsten wire may be avoided by the simple expedient of making it of relatively large diameter and arranging the charge so that the solubility of the molten aluminum for tungsten can be satisfied without dangerously reducing the diameter of the wire.

It might be expected that some of the dissolved tungsten would boil away, especially since its spectrum has been observed during evaporation.[25] In order to test this point, a coil was weighed before and after evaporating several charges of aluminum. Instead of a loss in weight, an increase was observed, indicating that some aluminum had

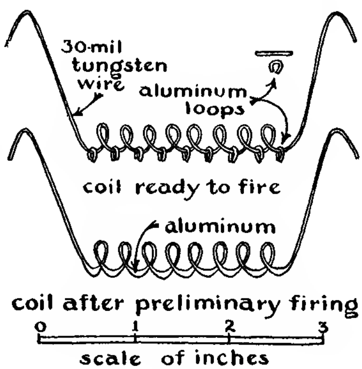


Fig. 12.

[24] Strong, J., *Phys. Rev.*, *43*, 498 (1933).
[25] Gaviola, E., and Strong, J., *Phys. Rev.*, *48*, 136 (1935).

diffused into the tungsten. However, extended heating in vacuum at a very high temperature decreased the weight, until, within the experimental error, it became the same as in the beginning. A chemical analysis of the condensed metal film was made to test whether or not tungsten is evaporated. The analysis gave no definite indication of tungsten. A concentration of 0.03 per cent by weight was

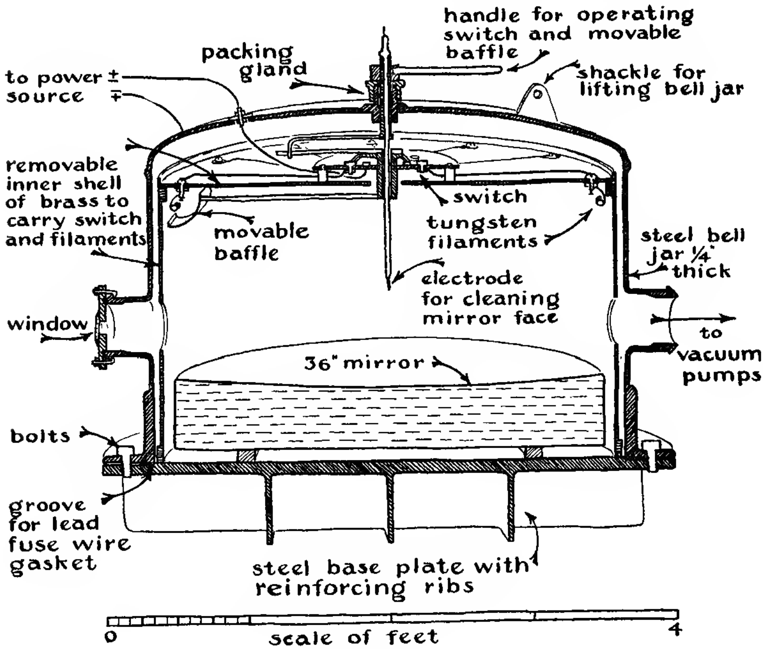


Fig. 13.

detectable. The tungsten which is dissolved thus appears to be almost completely precipitated back onto the coil as the evaporation proceeds. Although it may not be deposited back in exactly the same place, it does compensate in a large measure for the decrease in diameter of the tungsten wire.

The arrangement used at first for aluminizing mirrors at the California Institute of Technology is shown in Figs. 11 and 12. It is in the form of a helix, consisting of 10 turns of 30-mil tungsten wire, $\frac{5}{16}$ of an inch in diameter and pitched

4 turns to the inch. A **U**-shaped piece of aluminum wire 1 mm in diameter and about 10 mm in total length is clamped to each turn as is shown in Fig. 11. A potential of 20 volts applied to the coil in vacuum for 4 seconds prefuses these pieces as shown in Fig. 12. At this stage, surface tension keeps the molten aluminum from dropping. This prefusion also serves to free the metal from oxide and other impurities. It is customary to make a separate run in order to effect this fusing of the aluminum to the tungsten

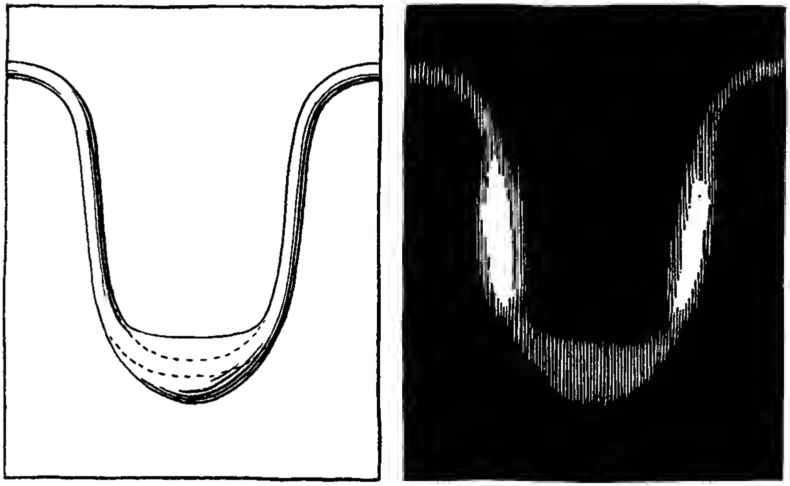


Fig. 14.

wires. In the 40-inch tank (see Fig. 13), however, the coils are covered by a baffle during the preliminary firing. The aluminum is finally distilled from the coils by applying the same voltage to each coil for about 15 seconds.

Actually, the aluminum does not evaporate from the fused metal but from the adjacent tungsten wire. This is clearly shown by the "self-photograph" of the filament reproduced in Fig. 14. This "self-photograph" was recorded on glass with the molecular rays of aluminum passing through a pinhole.

A recently developed evaporation source allows a much

higher rate of evaporation of aluminum with less tendency to burn out or drop molten aluminum. The new source uses three or four 20-mil tungsten wires twisted together as shown in Fig. 15. The metal charge, applied as illustrated in Fig. 11, flows out to fill the space between the wires when heat is applied. The aluminum covers the tungsten completely, so that a minimum "ratio" of heat radiation to molecular radiation of aluminum is achieved.

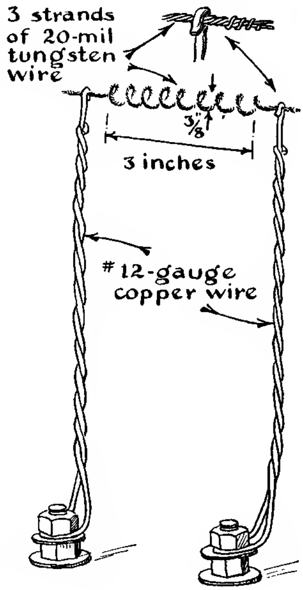


Fig. 15.

Fig. 16 shows the form by which the new source is applied to the evaporation of gold. When the gold melts in the "cup," it is drawn out to coat the tungsten and it fills up the spaces between wires from one end to the other.

For evaporation of silver and copper the source should be made from molybdenum rather than tungsten, as the latter metal is not easily wet with silver and copper.

For evaporation of the platinum metals, a unit similar to the one shown in Fig. 15 is made up of three 20-mil tungsten wires and one platinum metal wire of the same diameter. The "ratio" of heat to metal radiated is a minimum. Furthermore, the awkward process of electroplating the platinum on the filament is avoided. The evaporation should proceed slowly, even from this source, because if too much current is applied, the evaporation is no longer smooth, and globules of metal are discharged from the source.

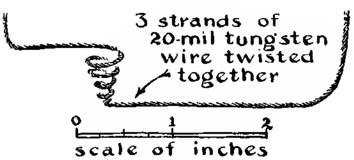


Fig. 16.

Chromium is easily evaporated from a source like the one shown in Fig. 16. A piece of the metal is put in the "cup" and is preheated in an atmosphere of hydrogen or helium to fuse it and distribute it over the tungsten. Various other evaporation sources are illustrated in Figs. 17 to 20.

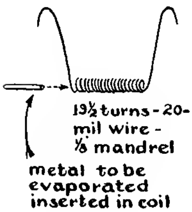


Fig. 17.

Vacuum equipment. The evaporation process is carried out in a vacuum of 10^{-3} mm of mercury or better. For small mirrors the necessary vacuum may be obtained with a kinetic pumping system such as the one shown in the previous chapter. The 40-inch tank, Fig. 13, shows the type of equipment used at the California Institute of Technology for larger mirrors. Still larger systems have been used.[26]

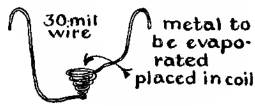


Fig. 18.

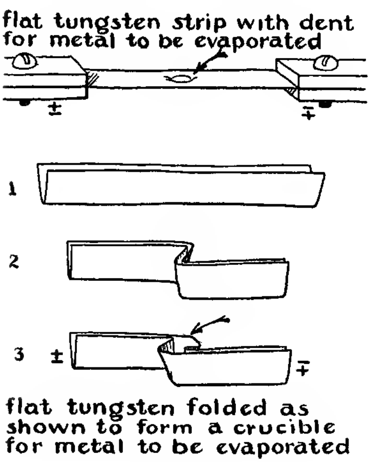


Fig. 19.

The cleaning electrode shown in Fig. 13 allows the vacuum vessel, containing the mirror, to be filled with a glow discharge during the preliminary evacuation with the roughing pumps; and this discharge effects the final cleaning of the mirror face.

It is recommended that the aluminum be evaporated soon after a nonconducting vacuum has been reached, in

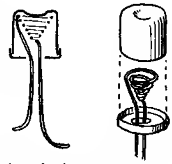
[26] Strong, J., *Astrophys. J.*, *83*, 401 (1936).

Metal tanks of seamless steel are available from the Eclipse Fuel Engineering Company (Los Angeles agent, James H. Knopf) in the same form as bell jars. After the foot is machined, they are suitable for sealing to a base plate to form a good vacuum container for evaporation. It is advisable to clean the tank inside and out by sand blasting and to coat it inside with Apiezon wax "W" and outside with Glyptal lacquer.

order to obtain maximum tenacity between the aluminum film and the glass. Also, this procedure yields harder films.

Uniform films. In order to obtain a uniform coat on large mirrors, aluminum is evaporated from several tungsten sources suitably arranged, rather than from one movable source.

The evaporation of polonium in a high vacuum from a point source has been investigated by Bonét-Maury.[27] This metal was chosen on account of its radioactivity. He found that the condensation on a plane surface is proportional to the inverse square of the distance from the source, and to the cosine of the angle between the normal to the surface and the line connecting the surface with the source. We may assume that the same is true of other metals which have a low vapor pressure at room temperature.



tantalum cap to enclose coil may be used for evaporating oxides or the dent in the top used for metals

Fig. 20.

Starting with this assumption, we may consider the distribution of the film thickness τ produced by various experimental arrangements. In the case of evaporation to the inside surface of a sphere of radius ρ from a point source of vapor at its center, the situation is very simple. We get a uniform film of which the thickness τ_0 is

$$\tau_0 = \frac{m}{4\pi\partial\rho^2}. \tag{1}$$

Here m is the mass of metal evaporated and ∂ is its density.

The film thickness at P on a plane surface at the normal distance ρ from a point source of evaporation is

$$\tau_P = \frac{m}{4\pi\partial r^2}\cos\theta = \tau_0\left(\frac{\rho}{r}\right)^3. \tag{2}$$

Here τ_0 is the thickness at P, r is the distance from the source to P, and θ is the inclination of the surface P to the molecular rays emitted by the source which impinge on it there.

[27] Bonét-Maury, P., *Ann. de Physique, 11*, 253 (1929).

The film thickness produced on a plane surface by a circular array of vapor sources can be determined by applying the above formula to each of the sources. (See Fig. 21.) If there are N coils spaced uniformly around a circle at a distance ρ from the surface to be coated, the film thickness on the surface at P, which is at a distance a from the intersection of the axis of the circle with the face of the mirror, is given by the expression

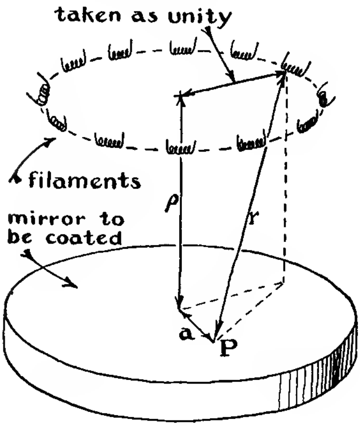


Fig. 21.

$$\tau_P = \frac{M\rho}{4\pi\partial N}\sum_1^N \frac{1}{r_i^3}. \tag{3}$$

Here M is the total mass of metal evaporated, and r is the distance from P to the coil represented by the summation index i.

Dr. Edward M. Thorndike made the same calculation, assuming a continuous circular source. The thickness is given in this case by

$$\tau_P = \frac{M\rho}{8\pi^2\partial}\int_0^{2\pi}\frac{d\theta}{r^3}. \tag{4}$$

Here the point source at distance r from the point P is replaced by a line source represented by the angle element $d\theta$ at distance r, as before. This calculation involves the integration

$$\int_0^{2\pi}\frac{d\theta}{r^3} = \int_0^{2\pi}\frac{d\theta}{(1 + a^2 + \rho^2 - 2a\cos\theta)^{3/2}} =$$

$$\frac{4}{[(a-1)^2 + \rho^2]\sqrt{(a+1)^2 + \rho^2}}\,E\left(\frac{2\sqrt{a}}{\sqrt{(a+1)^2+\rho^2}}\right), \tag{5}$$

in which E represents the elliptic function.[28] Values of this integral calculated by Thorndike are given in Table IV.

[28] Bierens de Haan, David, *Nouvelles tables d'integrales definies*, Table 67, Eq. 3, page 102. Leyden: P. Engels, 1867.

TABLE IV

VALUES OF $\int_0^{2\pi} \frac{d\theta}{r^3}$ FOR VARIOUS PARAMETERS

a	$\rho = \frac{1}{2}$	$\rho = 1$	$\rho = 1.1$	$\rho = 1.2$	$\rho = 2$	$\rho = 4$
0.00	4.50	2.22	1.91	1.65	.560	.090
0.25	4.82	2.24	1.93	1.65	.555	.090
0.50	3.96	2.29	1.93	1.63	.540	.088
0.75	7.74	2.28	1.89	1.57	.515	.085
0.80	....	2.27	....	....	....	....
0.90	....	2.22	....	....	....	....
1.00	8.28	2.11	1.74	1.45	.480	.082
1.50	3.40	1.38	1.09	1.02	.385	.072
2.00	1.20	0.74	0.67	0.61	.285	.068
3.00	0.28	0.24	0.23	0.22	.145	.050

For convenience, the radius of the circular source is here taken as unity. We see from this table that for $\rho = 1$ the film is quite uniform as far out from the center as $a = 1$. This case was realized in the 40-inch aluminizing tank by a circular array of twelve of the standard coils (see Fig. 12) spaced around a circle 36 inches in diameter, 18 inches above the face of the astronomical reflector to be coated (Fig. 22). Tests of transmission of a film produced with partially loaded coils confirmed the calculation, since the coat exhibited the expected uniformity.

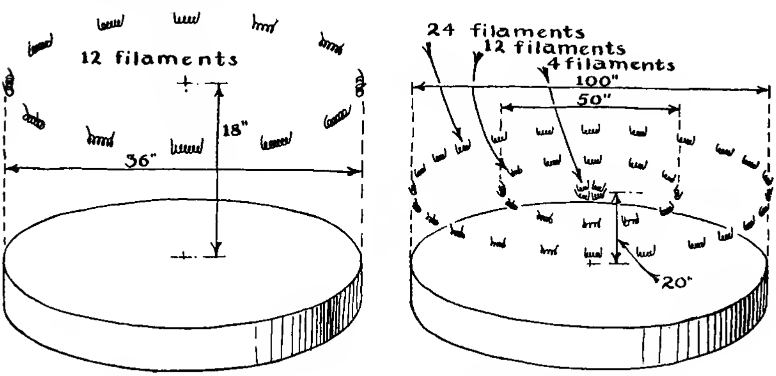


Fig. 22. Arrangements of evaporation coils for large mirrors.

In a larger 108-inch tank it was not convenient to use a similar array of coils spaced 50 inches from the face of the mirror. Instead, three arrays were used, each about 20 inches from the mirror. The arrangement is shown in Fig. 22. From the expressions developed above, as well as from actual tests, it was found that four coils in the center, twelve on a circle of 50 inches in diameter, and twenty-four on a circle of 100 inches in diameter gave the proper loading. This arrangement produced a uniform film of proper thickness on a 100-inch mirror, the film being just a little thicker than that required to be opaque to sunlight. It is desirable to have this thickness (about 1000 Å), since much thicker films are more easily scratched, while thinner ones may in time become transparent as a result of the gradual growth of thickness of the oxide layer which forms on the aluminum coat.

Parabolizing a spherical mirror with aluminum. As soon as the technique for the attainment of uniform films was perfected, it became possible to prepare nonuniform films, with the thickness of the film varying in just the manner required to parabolize a spherical mirror. The difference τ between the circle and parabola illustrated in Fig. 23 is given to close approximation by the expression

$$\tau = y^2(y_0^2 - y^2)\frac{1}{8R^3}, \tag{6}$$

where y is the ordinate and R is the radius of curvature of the circle. y_0 represents the ordinate where the two curves intersect. The difference is zero at $y = 0$ and at $y = y_0$ and has a maximum at $y = y_0/\sqrt{2}$.

If a spherical mirror of diameter $2y_0$ (represented by the surface generated by rotation of the circle in Fig. 23 about the X axis) is to be transformed to a paraboloidal surface (the surface generated by rotation of the parabola), it is evident from Eq. 6 that it is necessary to add to the sphere a zone of aluminum which has its maximum thickness at

$y = y_0/\sqrt{2}$, tapering off on either side of this as required by the equation.

The maximum thickness of aluminum, $\tau_{\text{max.}}$, required depends naturally upon the radius of curvature of the

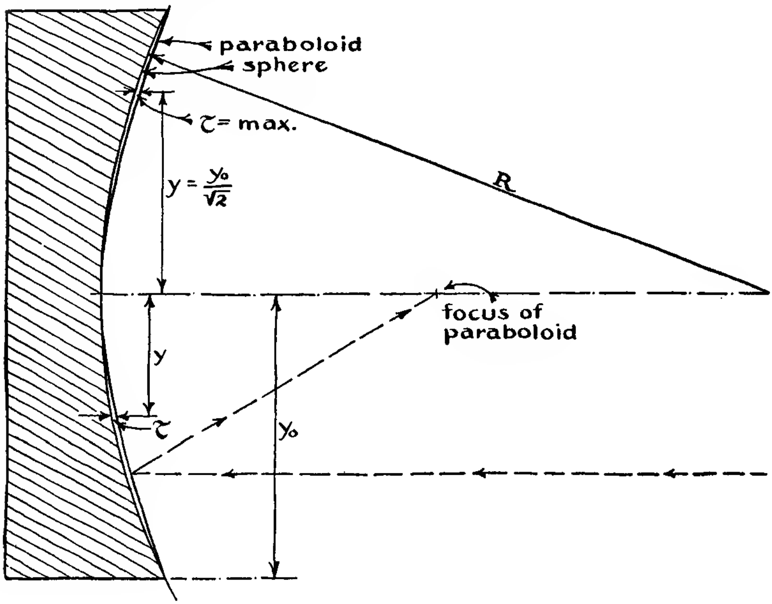


Fig. 23.

sphere, R. The connection between $\tau_{\text{max.}}$, R, and y_0 is given by the expression

$$\tau_{\text{max.}} = \frac{y_0^4}{32R^3}, \tag{7}$$

or, in terms of its f value,

$$\tau_{\text{max.}} = \frac{y_0}{2048f^3}. \tag{8}$$

Inasmuch as it is possible to put down films of aluminum to 1μ thickness and greater, it is possible to parabolize a 12-inch mirror $f/6$, which requires a maximum thickness of only 0.34μ of aluminum. This is not an uncommon example encountered in astronomical mirrors.

The correct procedure for applying such a parabolizing film is first to compute the thickness and distribution of the aluminum film produced by a point source positioned opposite the center of the mirror as shown in Fig. 24. This

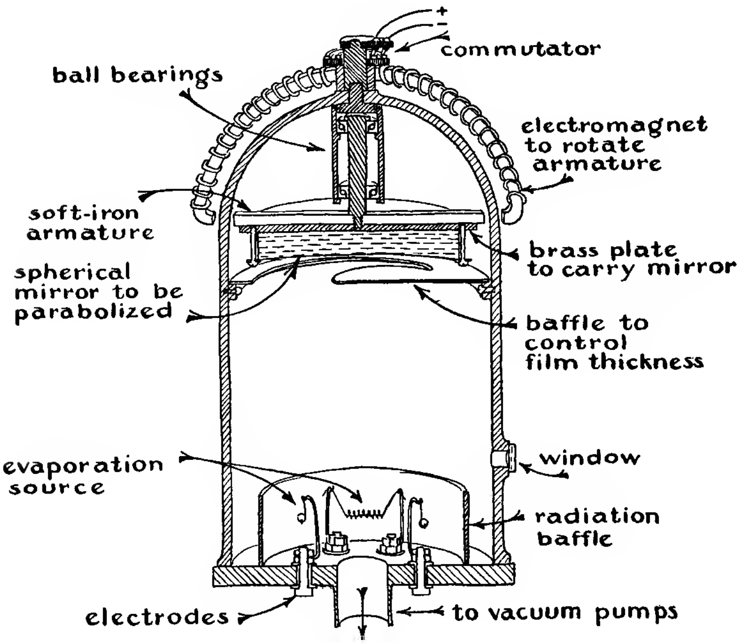


Fig. 24.

can be done by the use of the formula given below for the thickness of aluminum τ produced at a distance y from the center of the mirror.

$$\tau = \frac{my}{34d^3}. \tag{9}$$

Here m is the total mass of aluminum evaporated, in grams, and d is the distance between the source and the point in question on the mirror face.

A baffle of the shape illustrated by Fig. 25 is then cut from thin sheet brass and placed directly in front of the mirror as shown in Fig. 24. This baffle can be rotated, or, what is

more convenient, it may be fixed and the mirror rotated as shown in Fig. 24. The baffle is so designed as to modify the thickness which would otherwise be obtained (given by Eq. 9), so that it will conform with that required by Eq. 6. The baffle will have zero angular opening at the center and edge and a maximum opening very near to $y = y_0/\sqrt{2}$. It is to be remembered that the effect of the baffle in a given zone is to decrease the thickness by a factor which is the ratio of the quantities, 360° minus the angular opening of the baffle opposite the particular zone in question, to 360°. In order to avoid astigmatism, the mirror is rotated a great many times during the deposition.

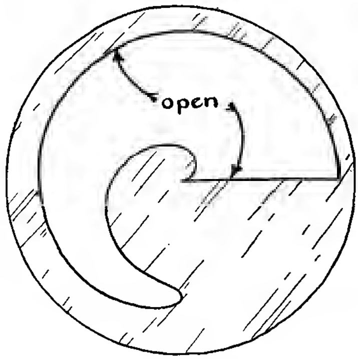


Fig. 25.

It is necessary, for some reason not yet clearly demonstrated, to evaporate slightly more aluminum than the simple theory outlined above predicts. The procedure in this case is to deposit some metal (about the theoretical amount) and then test the mirror. On the basis of the Foucault test, an additional amount is evaporated, and so on until the required figure is obtained. If too much metal is added, the coat can be washed off with caustic soda. Usually the mirror can be finished on the second attempt. When several mirrors, all alike, are to be parabolized, this preliminary testing may be done once for all.

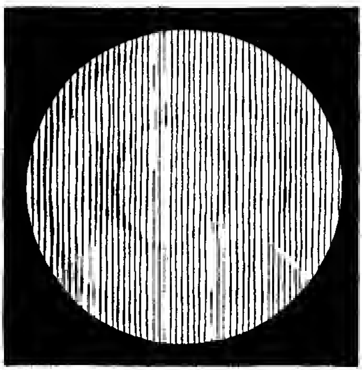


Fig. 26. Starting sphere tested at the center of curvature.

Figs. 26, 27, and 28 show focograms of a mirror parabolized by this method. It was originally a sphere true to $\frac{1}{20}$ of a wave length of green light, as the first focogram (Fig. 26), taken at its center of curvature, shows. This sphere was $152\frac{1}{4}$ inches in radius of curvature. $2y_0$ was $12\frac{3}{8}$ inches. The next focogram, Fig. 27, shows it at its mean focus when tested with parallel light with the aid of a testing flat, obviously in need of parabolizing to give a good knife-edge cutoff. After it was parabolized with a coat of aluminum, it appeared as shown in the third focogram, Fig. 28. Here, again, it exhibits a true figure of revolution, this time a parabola true to less than $\frac{1}{20}$ of a wave length of green light.

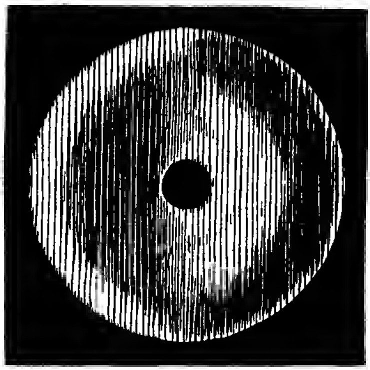


Fig. 27. Sphere tested at its mean focus.

Mirrors imperfectly figured by conventional methods can be improved by this procedure. In this case the baffle design is determined by a preliminary quantitative survey of the mirror with a knife-edge testing outfit. (See Chapter II.)

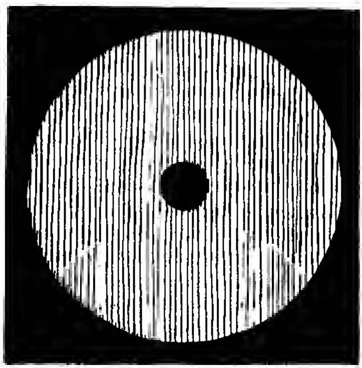


Fig. 28. Sphere after parabolizing with an aluminum film. Tested at the focus.

It is possible to apply a thin film of aluminum to a convex sphere and transform it to a hyperbolic figure of revolution for use as the secondary mirror in a Cassegrain telescope. The formula for the difference between the hyperbola, or any conic of eccentricity ϵ, and the sphere tangent to it at the center and touching it at the radius distance y_0 is

$$\tau = \frac{\epsilon^2 y^2 (y_0^2 - y^2)}{8R^3}. \tag{10}$$

Eq. 6 for the parabola is Eq. 10 when $\epsilon = 1$. To obtain a hyperbola, it is necessary to have the aluminum thick at center and edge with a minimum at $y = y_0/\sqrt{2}$. The baffle to effect this is just the inverse of the one shown in Fig. 25, being open where the other is opaque and vice versa. The further details of the process are described in a paper by Strong and Gaviola and in the paper of Gaviola on the quantitative use of the knife-edge test.[29]

Partially reflecting films. Partially reflecting films of silver and aluminum are useful for dividing a beam of light in many optical instruments such as color cameras and interferometers.

Figs. 29 and 30 show the reflection and transmission characteristics of silver and aluminum films obtained by the

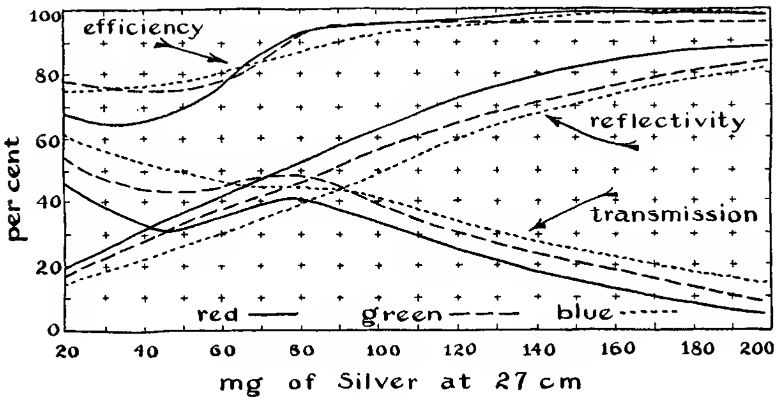


Fig. 29.

evaporation of various amounts of metal. The curves illustrate the color characteristics of the films and their efficiencies. They also indicate approximately the amount of metal to be evaporated to obtain any desired ratio of reflection to transmission. The curves for silver refer to

[29] Strong, J., and Gaviola, E., *J.O.S.A.*, *26*, 153 (1936).
Gaviola, E., *J.O.S.A.*, *26*, 163 (1936).

fresh deposits, whereas the curves for aluminum apply to films about 6 months old, which have more or less attained their equilibrium optical characteristics.

The reproducibility with which any given film can be prepared from the information given in Figs. 29 and 30 is

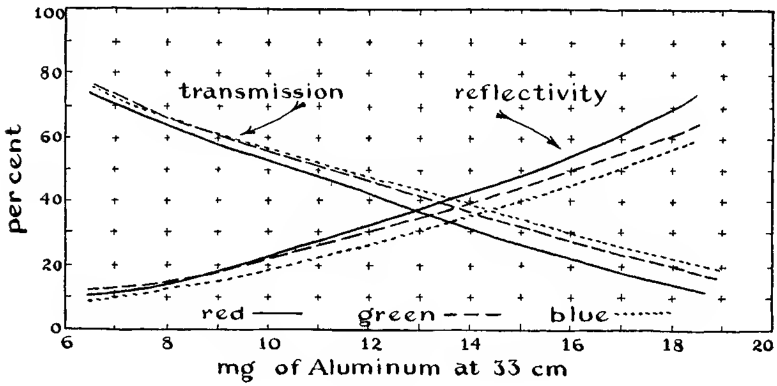


Fig. 30.

unfortunately not very great. The variations to be expected are greater in the case of aluminum.

The films from which the curves in Figs. 29 and 30 were obtained were evaporated with a vacuum of 1 to 5 $\times$ 10^{-5} mm, the mirror distance being 33 cm in the case of aluminum and 27 cm in the case of silver. A source like the one shown in Fig. 17 was used for silver. The metal was in the form of a 40-mil wire. A straight, horizontal 40-mil tungsten wire served as the evaporation source for aluminum as shown in Fig. 31. The metal was a weighed U-shaped piece of wire pinched onto the center of the tungsten wire.

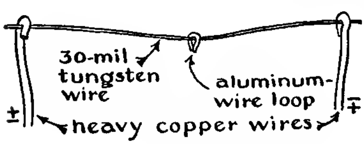


Fig. 31.

Silver films have a greater efficiency than aluminum films, and they are, accordingly, best for coating Farby and Perot interferometer plates. They may be protected from the

tarnishing gases in the atmosphere by a thin layer of calcium fluoride or quartz.

The calcium fluoride (or quartz) films should be about $\frac{1}{4}$ of a fringe in thickness. If a copper sheet is placed close to the evaporation source, it is possible to count the fringes as they are formed on this sheet by the evaporated calcium fluoride (or quartz). The square of the ratio of the distance of the copper to that of the silver gives the ratio of film thickness of calcium fluoride (or quartz) evaporated onto these two surfaces. The evaporation of calcium fluoride (or quartz) is stopped after an appropriate number of fringes have appeared on the copper.

A thin film of aluminum on the silver will oxidize to a protecting layer of aluminum oxide on exposure to the air. The proper amount of aluminum to be evaporated is about one-sixteenth the amount required to give a half-transmitting coat. Accordingly, the proper amount of aluminum may be gauged by means of an auxiliary glass plate positioned at one-fourth the silver film distance from the evaporation source. The proper amount of aluminum is evaporated when the film on the auxiliary glass plate appears to be about half-transmitting.

CHAPTER V

The Use of Fused Silica

BY

H. V. NEHER

General remarks on fused quartz. Formerly made only in rod and tube form, fused quartz[1] is now often employed as a substitute for glass in chemical ware, and most of the common pieces used in chemistry are now obtainable in this material. Such articles as flasks, beakers, dishes, plates, and so forth, are in fairly common use.

Apparatus made from fused quartz has two chief advantages over that made from glass. The low thermal expansion coefficient eliminates all fear of breakage due to rapid temperature changes. A hot piece of quartz plunged into water suffers no ill effects. Also, its relatively high melting point makes possible the study of reactions which would be more difficult with glass.

As will be pointed out later, many of its properties make it valuable in instruments of various kinds and when constancy is a prime requisite. One particularly valuable property of fused quartz is its extremely low loss of energy due to internal friction when stresses are applied. The loss amounts to only 10^{-3} of that in the best of the metals. Another property of value lies in its constancy of length. It not only has an extremely small thermal expansion coefficient, but returns to its original length after having been heated or cooled.

The chief disadvantage of fused quartz is its high cost,

[1] Fused quartz is obtainable from the Thermal Syndicate and the General Electric Company. Each carries a large stock of quartz products and will make special pieces on demand.

due mainly to the fact that it has a high melting point and demands special methods for its manufacture. The fact that it fuses with difficulty makes the working of tubing greater than an inch in diameter more or less impractical in the laboratory. Although an oxyhydrogen flame becomes useful when working large pieces of quartz, small pieces can be worked easily with an oxy–natural gas flame. An ordinary Bunsen burner flame using natural gas is hot enough to soften small pieces.

A very useful property discovered by C. V. Boys[2] in 1889, and discussed in detail later, is that fused quartz can be drawn into fine fibers which have remarkable strength. Fibers of any size down to 1μ (0.0001 cm) diameter or less can be easily and rapidly produced. No other vitreous material can in any way approach fused quartz in performance when made into these fine fibers.

Chemical properties. Fused silica at room temperature is inactive to practically all chemicals except hydrofluoric acid and the alkalies. However, at high temperatures it reacts with most metallic salts, forming silicates. This is due to the fact that silicon dioxide is an acid in the general sense of the term, and as such reacts vigorously at high temperatures with metallic oxides which are bases. The noble metals do not form silicates, and a quartz fiber covered with gold may be heated until the gold evaporates, without harming the fiber.

Physical properties. *Thermal properties.* The coefficient of thermal expansion of fused quartz rod under no stress has been measured with considerable accuracy.[3] The mean values near room temperature, defined by $\alpha = (1/l)(\Delta l/t_2 - t_1)$, are given in Table I. For comparison, steel has a coefficient of 10.1×10^{-6}°C.$^{-1}$, or 25 times as large, while for Invar α is about 0.9×10^{-6}°C.$^{-1}$. The coefficient of thermal expansion has not been measured for various sizes of fibers under varying amounts of strain.

[2] Boys, C. V., *Roy. Soc., Phil. Trans.*, *143*, 159 (1889).
[3] Kaye, G. W. C., *Phil. Mag.*, *20*, 718 (1910).

TABLE I

THE MEAN VALUES OF THE COEFFICIENT OF THERMAL EXPANSION OF FUSED QUARTZ NEAR ROOM TEMPERATURE, DEFINED BY $\alpha = (1/l)(\Delta l/t_2 - t_1)$

Temperature (°C.)	α ($\times 10^{-6}$ °C.$^{-1}$)
− 40 to 0	0.31
0 to 30	0.42
30 to 100	0.52
100 to 150	0.58

The coefficient of thermal hysteresis of fused quartz is less than for any other known material. If a substance of length l is heated from a temperature t_1 to a temperature t_2 and allowed to cool to t_1, then $(1/l)(\Delta l/t_2 - t_1)$, where Δl is the residual difference in length, is a measure of the thermal hysteresis. For quartz, this quantity is -1 to -5×10^{-9} °C.$^{-1}$; that is, it contracts more than it expands. In comparison, Invar has a similar coefficient of -100×10^{-9} °C.$^{-1}$. This property makes fused quartz particularly valuable when it is necessary to maintain dimensions accurately.[4]

If fused quartz is held at a temperature above 1200°C. for some time, crystallization gradually takes place, beginning at the surface and working inward. As the temperature is raised, the crystallization becomes more rapid until a temperature is reached at which the crystals melt. When quartz is worked locally in a flame, a milky surface will form between the soft quartz and the cool portion. This is probably due to condensation of evaporated quartz and does no harm to the material except in appearance.

Elastic properties. The normal coefficient of elasticity, or the reciprocal of Young's modulus for quartz rod at room

[4] For a discussion of the behavior of metals and quartz used as standards of length the reader is referred to Glazebrook, Sir Richard Tetley, editor, *Dictionary of Applied Physics*, Volume III, pages 471–475. New York: The Macmillan Company, 1922–1923.

temperature, was measured first by Boys. This coefficient is defined by

$$\frac{1}{Y} = \frac{1}{l}\frac{\Delta l}{\Delta S_n},$$

where Y is Young's modulus and S_n is the normal stress. Boys found the value $Y = 5.2 \times 10^{11}$ dynes cm^{-2}, which is very near the most recently determined values for fibers from 50μ to 100μ in diameter. Young's modulus varies with the size of the fiber, becoming greater as the size of the fiber diminishes. This variation can be expressed by

$$Y = \frac{27 \times 10^{11}}{d} + 5.9 \times 10^{11} \quad \text{dynes cm}^{-2},$$

where d is the diameter of the fiber in microns. This relation fails to hold, giving values too large, for fibers less than 10μ in diameter. Experimental values of Y for various sizes of fibers are given in Table II. The increase in modulus of elasticity with decrease in size is due to the importance of the surface layer for the smaller fibers, which has a different elastic constant.

TABLE II

BREAKING STRENGTH, YOUNG'S MODULUS, Y, MODULUS OF RIGIDITY, Z, AND $\Delta l/l$ FOR FAILURE FOR DIFFERENT SIZES OF QUARTZ FIBERS

Diameter (μ)	Breaking Strength ($\times 10^{11}$)	Y ($\times 10^{11}$)	Z ($\times 10^{11}$)	$\frac{\Delta l}{l}$ for Failure
1.5	0.90	..	..	..
2.0	0.80	..	..	..
3.0	0.65	11.1	6.6	0.059
4.0	0.55	10.3	6.1	0.054
5.0	0.48	9.8	5.8	0.049
7.0	0.39	9.0	5.3	0.043
10.0	0.30	8.5	4.8	0.035
15.0	0.23	7.9	4.2	0.029
20.0	0.17	7.6	3.9	0.022
30.0	0.145	7.1	3.5	0.020

Data taken from Reinkober, O., *Phys. Zeits.*, *38*, 112 (1937).

These are mean values; values of individual fibers may be as much as 20 per cent higher or lower than those given. Units are in dynes cm^{-2}.

The tangential coefficient of elasticity, or the reciprocal of the rigidity modulus, for solid rod of radius r and length l, is defined as

$$\frac{1}{Z} = \frac{1}{2l}\,\frac{\Delta(\phi r)}{\Delta S_t},$$

where S_t is the tangential stress and ϕ is the angle of twist of the rod. For a uniform solid round rod $S_t = (L/r)/(\pi r^2)$, where L is the applied torque and r is the radius. Z has a minimum value of 3×10^{11} dynes cm^{-2} but depends, as does Y, on the size of the fiber, as shown in Table II.

Two other elastic quantities are very often useful. The first indicates how much a fiber can be stretched before it breaks, that is,

$$\left(\frac{\Delta l}{l}\right)_{\text{for failure}} = \frac{(S_n)_f}{Y},$$

where $(S_n)_f$ is the normal stress for failure. Values of $\Delta l/l$ for failure are given in Table II. These apply only to fresh, clean fibers or those which have been kept perfectly clean and dry. (See below as to how to preserve fibers.) As far as is known, no other material approaches this factor. For the best nickel-vanadium steels the ratio is about 0.01. A comparison of Young's modulus for each material shows that quartz fiber compares favorably in strength with the strongest materials known.

The second quantity indicates how much a fiber can be twisted without failure, that is,

$$\left(\frac{r\phi}{l}\right)_{\text{for failure}} = \frac{(S_t)_f}{Z} \cong 0.05$$

for fibers up to 20μ in diameter, where $(S_t)_f$ is the tangential stress for failure. This ratio also increases as the size of the fiber decreases. Thus, a fiber 5μ in diameter can be twisted through at least 20 revolutions per centimeter of length before it fails. It should be remarked that the elastic limits for both normal and tangential stresses are coincident with the point of failure.

Another property of quartz which enhances its value for electrometer and other suspensions is its low internal viscosity. If a fiber is twisted through an angle ϕ, then the shearing stress is not strictly a constant but depends on time, thus:

$$S_t = Z\frac{\phi r}{2l} + \frac{\eta}{2}\frac{d}{dt}\left(\frac{\phi r}{l}\right).$$

The coefficient η is a measure of the internal friction, or viscosity. Some representative values[5] are given in Table III.

TABLE III

VISCOSITY OF VARIOUS SOLIDS

Material	Viscosity ($\times 10^9$ poises)
Silver	12.5
Gold	17.0
Nickel	1.65
Platinum	1.75
Tungsten	9.37
Zinc	411.0
Quartz	0.001 (approx.)

If a fiber of length l and radius r is allowed to oscillate in a vacuum with a body of moment of inertia I suspended from the lower end, and if T is the period and λ the logarithmic decrement of the vibration, the coefficient of viscosity in poises is given by

$$\eta = \frac{8Il\lambda}{\pi r^4 T}.$$

If such a torsion pendulum has a period of 2 seconds, it will lose about 10 per cent of its amplitude in 24 hours.

Thus η, as defined above, should be as small as possible if the internal losses are to be kept at a minimum.

[5] Honda, K., *Phil. Mag.*, *42*, 115 (1921).
Iida, K., *Bull. Earthquake Res. Inst. of Tokyo University*, *13*, 665 (1935).

Thermal-elastic properties. Both Young's modulus and the rigidity modulus for fused quartz depend on temperature. Each becomes greater with moderate increase in temperature. Boys[6] gives the coefficient of Y as 1.3×10^{-4}°C.$^{-1}$, and for Z it is the same. For very accurate work any instrument using quartz fiber should be calibrated at more than one temperature.

Hardness. Fused silica has a hardness of 7 on the 1 to 10 scale. It is thus harder than glass and also harder than most of the metals.

Surface tension of molten silica. If a fiber is heated until the quartz becomes quite soft, it will tend either to shrink and enlarge at the point of heating or to pull apart, depending on the tension. We may define the surface tension as the force per unit of circumference tending to pull the fiber together. This varies with the temperature, but an average value will be 250 dynes cm^{-1}. In comparison, glass has a surface tension of 140 to 160 dynes cm^{-1}.

Electrical properties. When fused quartz is clean and dry, it is probably the best electrical insulator known. For this reason it is useful in such apparatus as electroscopes and electrometers, in which leakage must be reduced to a minimum. If used in the open air, quartz covered with the wax known as ceresin is still better than amber as an insulator. Care should be taken that the ceresin is that distilled from the natural mineral and not the synthetic material very often sold. When it is applied, the temperature of both the quartz and the ceresin should be from 80° to 100°C. for the first dip. Thicker coatings can be applied by allowing the quartz to cool before dipping again.

The absorption of electrical charge, or "soak-in," is extremely low, being less than 10 per cent of that for amber.

The use of quartz in the form of fibers. The remarkable property of retaining and even increasing its strength as it is drawn into fine fibers makes the number of applications of

[6] Glazebrook, Sir Richard Tetley, editor, *Dictionary of Applied Physics*, Volume III, page 699. New York: The Macmillan Company, 1922–1923.

quartz to fine instruments many and varied. Few scientists, it seems, have realized and appreciated its values. Stronger than any of the metals used for suspensions, with the exception of tungsten, it has the advantage that it can be made according to the specific requirements. Although some practice is necessary to acquire the proper skill, its acquisition would seem eminently worth while, considering the results that can be obtained.

Equipment useful in making and working with quartz fibers. A description of the torch burning natural gas and oxygen used by the author of this chapter will be given. If other gases are used, it may be necessary to modify the technique given below to meet the specific conditions.

The torch is made from a piece of brass tubing bent into the shape shown in Fig. 1 and having one end threaded for

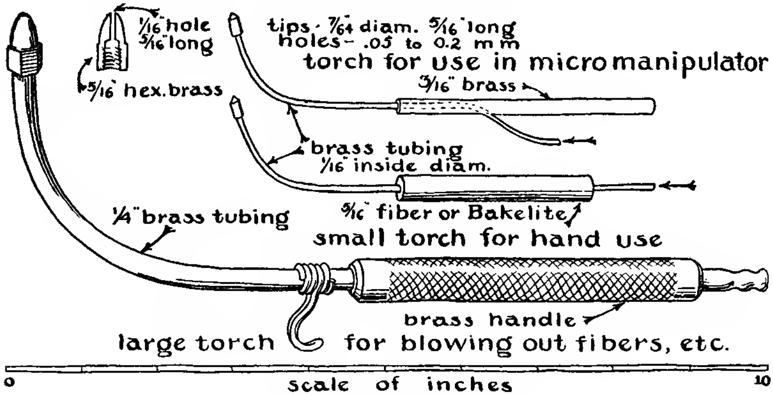


Fig. 1. Large and small torches for working fused quartz.

removable tips. The best size of opening for quartz work is about 2 mm in diameter. Other sizes of tips from 1 to 3 mm in diameter will be found useful. To produce the necessary long steady flame, the length of the hole in the tip should be at least five times its diameter. The oxygen and gas are mixed at some distance from the torch. An ordinary **T** is sufficient for this mixing. It is necessary to have a ready means of control for both the gas and the oxygen.

If the latter is under high pressure, a reduction valve in conjunction with a needle valve gives the best regulation. A combination of needle valves and **T** which has been found to give satisfactory service is shown in Fig. 2.

In using such a torch, care should be taken in lighting to turn the gas on first, light it, and then gradually turn the oxygen on until the proper flame is produced. To extinguish the flame, turn the oxygen off slowly and then the gas. Disregard of this procedure may result in a backfire into the line but usually does little damage except to sensitive nerves.

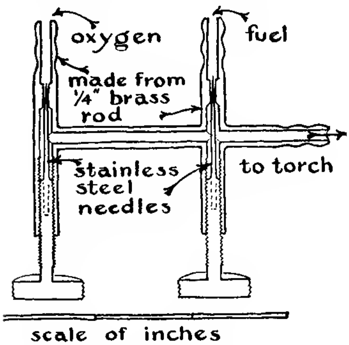


Fig. 2. Combination of needle valves and mixer.

The described torch is a useful adjunct to any laboratory, especially when supplied with tips of various sizes. It is ideal for working Pyrex glass as well as quartz. When quartz fibers are being made, the torch is held by a clamp so that the flame is vertical.

Indispensable in the working of small pieces of quartz is a small torch shown in Fig. 1, identical with the larger one except for size, and using the same gases, which are controlled by separate fine needle valves. The best metal tubing for this torch is brass or copper $\frac{1}{16}$ inch in internal diameter. The gases are led from the mixer to the torch by $\frac{1}{16}$-inch rubber tubing. Small volumes throughout are important, or much time will be wasted in waiting for a change of gas mixture to arrive at the tip. The tips should be interchangeable and should have openings of from 0.05 to 0.2 mm in diameter. A slight modification of design (illustrated) permits the torch to be mounted and manipulated by mechanical means. The usefulness of this small torch will become apparent later.

In measuring the sizes of fibers, an ordinary microscope equipped with a scale in the eyepiece and having a magnifica-

tion of from 300 to 1000 is very useful. With some experience the sizes of fibers can be judged to within 20 to 50 per cent by the amount of scattered light, the way they weave in the air, and so forth, but in many cases the diameter is important, and an accurate means of determining their size is invaluable.

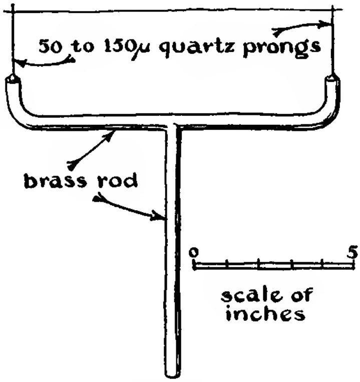


Fig. 3. A simple fork used for holding fibers while they are being mounted.

After blowing out a fine fiber, two places are marked, and the position of the intervening portion is thus determined by small tabs. Dennison's No. 251 tabs are recommended.

In many instances one works with fibers from a few centimeters to 10 or even 20 cm in length. In these cases the fibers are mounted on a two-pronged fork. This is easily made as shown in the sketch, Fig. 3. The end of

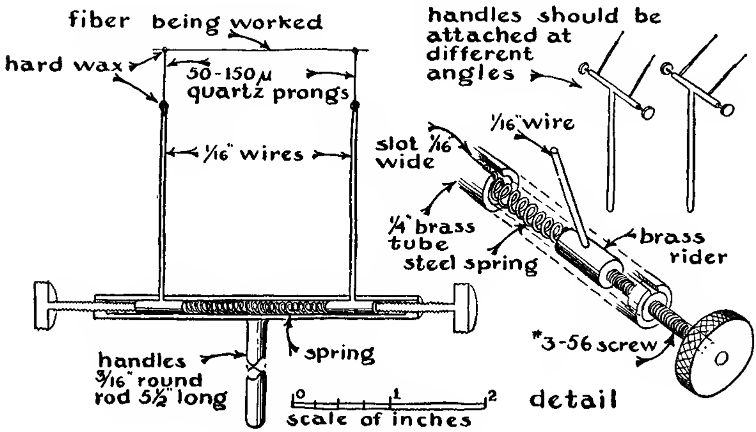


Fig. 4. Adjustable prong fork.

each prong is drilled, and a piece of quartz (50μ to 150μ) is put in with hard wax. The reason for the quartz tips is to

allow some freedom to the fiber, since the quartz tips will bend if the fiber is pulled one way or the other. Rigid supports result in many more broken fibers. The fiber is fastened to the tips with a small piece of hard wax.

In cases in which one fiber is melted to another, each will shrink, and the quartz will gather at the junction. It is necessary then to have two forks, each with movable prongs.

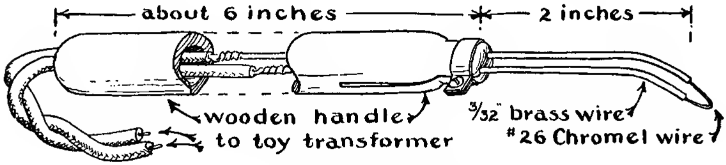


Fig. 5. Hot-wire holder.

The fork designed according to Fig. 4 has proved very satisfactory. If the handles are attached at different angles, the two forks can be worked together more easily.

A hot wire mounted as in Fig. 5 has many uses and is especially valuable in melting small pieces of wax. The resistance wire can be any one of several, such as platinum, German silver, Chromel, Nichrome, and so forth. It should be 24–26 B and S gauge. A toy transformer with variable voltage of from 1 to 6 volts is convenient for controlling the temperature. A foot switch is very useful, since both hands may be occupied when the heat is wanted.

In testing for conductivity of quartz fibers which have a coating of metal, a probe (see Fig. 6) with a fine platinum

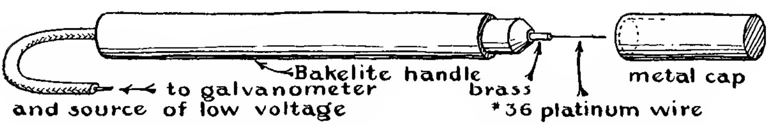


Fig. 6. Platinum probe for testing conductivity of metal-covered fibers.

wire tip finds a use. For such testing high voltages should not be used, since the resulting sparking will remove the metal from the fiber around the point of contact. Several volts applied through a 100,000-ohm resistance and a low-

sensitivity galvanometer will be found satisfactory for qualitative work.

Waxes are indispensable in fastening fibers either temporarily or permanently. For general use Dennison's hard red wax, DeKhotinsky wax, or flake shellac is recommended. If the wax is holding in place two or more fibers which are to have a metal evaporated or sputtered onto them, one of the latter two waxes should be used and heated until polymerization takes place, resulting in a material either difficult or impossible to melt. Otherwise the heat developed during the process of depositing the metal may cause the wax to soften and the fibers to be displaced.

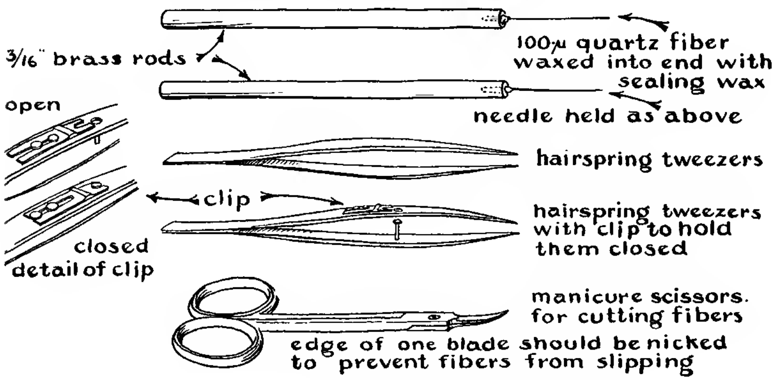


Fig. 7. Various instruments useful in fiber work.

In case it is necessary to hold a fiber temporarily and to maintain its desirable qualities, a wax must be used which, when heated, will completely disappear and not react in any way with the quartz. None of the products sold as waxes serve the purpose. An organic chemical which has the desired properties is diphenylcarbazide. It usually comes in powdered form and should be as pure as possible and especially free from inorganic materials.

In handling small pieces of wax, holding fibers, bending quartz fibers, and so forth, a piece of quartz 100μ in diameter and 2 to 3 cm long, waxed into the end of a metal rod, is very useful. (See Fig. 7.) It will also be found that a needle

mounted in the end of a metal rod has many uses. It is recommended that several such quartz and needle holders be available.

When working with small objects, tweezers of various sizes are very convenient. These can be obtained from jeweler's supply houses or from most houses supplying scientific apparatus. For very fine work, watch-hairspring tweezers such as #3C made by Dumont & Fils, Switzerland, are recommended. Also valuable in cutting fibers are small scissors. These may be a good grade of manicure scissors or dissecting scissors used in biological work. A nick should be made in one blade to prevent large fibers from slipping. If the scissors are guided by mechanical means, small fibers (up to 40μ) can be cut off as little as 0.01 mm at a time under a microscope.

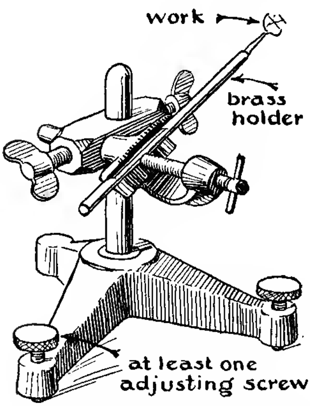


Fig. 8. Support for holding work or fixing the position of fibers.

In most fiber work it is necessary to fix the position of the fiber with some accuracy. Small tripods with adjustable feet, together with clamps and rods, as shown in Fig. 8, will serve to hold the various forks, needles, and so forth, used in the process of mounting the fibers. It is very difficult to hold a fiber still enough by hand, and it is always best to take advantage of mechanical devices wherever possible.

Very small fibers (1μ and less) can be easily seen by scattered light against a black background. Black velvet is one of the best. If the diameter of a fiber is to be measured under the microscope, a light background is needed; the scattered light against black gives a false impression of the size, since the actual outlines of the object cannot be seen.

To put a conducting coat of metal on quartz, any one of several methods can be used. The simplest, and one which is satisfactory for fibers down to 20μ in diameter, is to bake

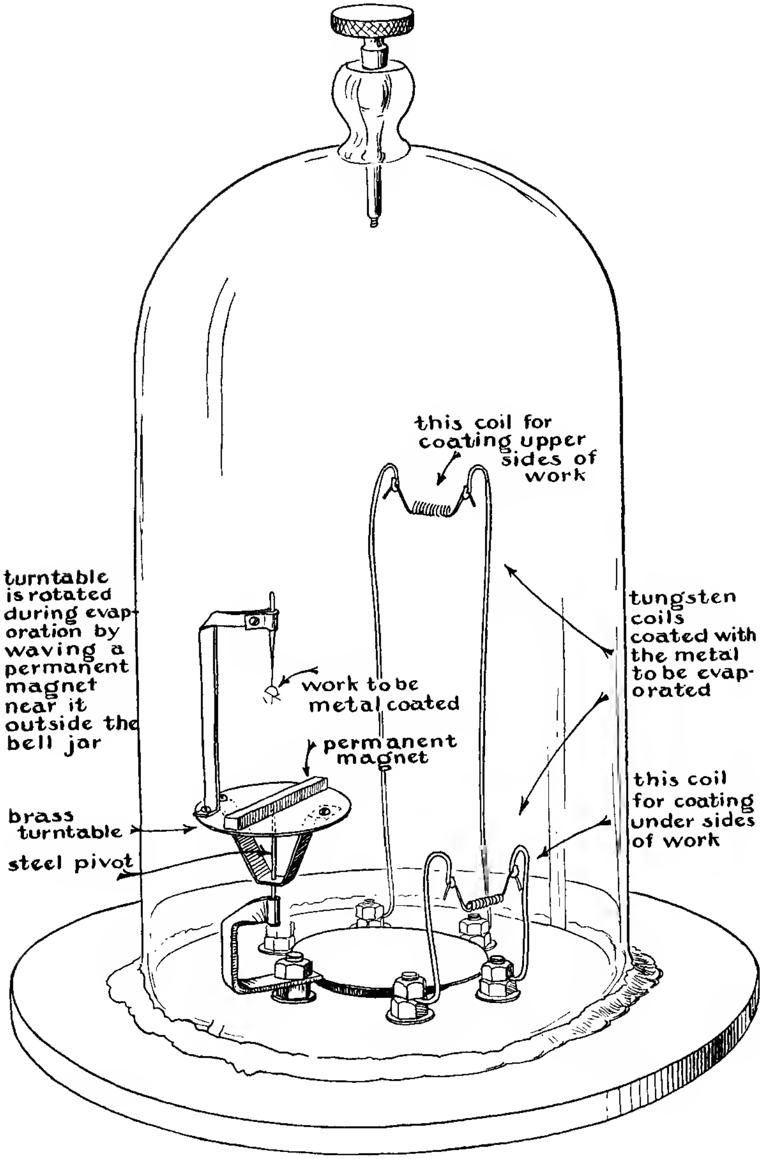


Fig. 9. This arrangement allows the evaporated metal to be deposited on all sides of the work.

the metal on, using any of the good china paints. Most of the noble metals—for example, platinum, gold, iridium, and so forth—can be obtained in this form. The paint is made by dissolving one of the metal salts in an organic liquid. China painters use this on their dishes and fire them to 700°C. The organic material disappears, and the metal compound decomposes, leaving behind a uniform coating of the metal. The thickness for each coat may vary from 0.05μ to 0.15μ, depending on the thickness of the original paint. Very adherent, electrically conducting coatings can be applied to glazed porcelain, glass, quartz, and so forth. The hot wire, held under small pieces of quartz fibers covered with these solutions, will bake them in a few seconds. If an attempt is made to treat small fibers in this way, it will be found that the solution collects into small drops along the fiber, and a disconnected coating results when it is baked.

Sputtering or evaporating the metal on are the most satisfactory methods and have the advantage that conducting coats can be applied to fibers of any size. In general it is desirable to arrange to coat the fibers on all sides. Evaporation is the easier and simpler of the two methods. (See Chapter III.) A suitable apparatus for this is shown in Fig. 9.

In working quartz it is absolutely necessary to use dark glasses to protect the eyes. Besides the brilliant glow, which in itself is bad for the eyes, the light is very rich in ultraviolet, which is especially harmful and may cause blindness through long exposure. The glasses should be gray in color, preferably, and have a transmission of from 10 to 20 per cent. Ordinary glass will cut out the ultraviolet, so that inexpensive dark glasses will suffice.

The writer has used for some time a set of three micromanipulators. Each has a three-jointed arm, which allows complete freedom in determining the position of the fiber. For fine adjustment, micrometer screws with divided heads give accurate motion in three mutually perpendicular directions. The accompanying illustration, Fig. 10, shows one of the three manipulators.

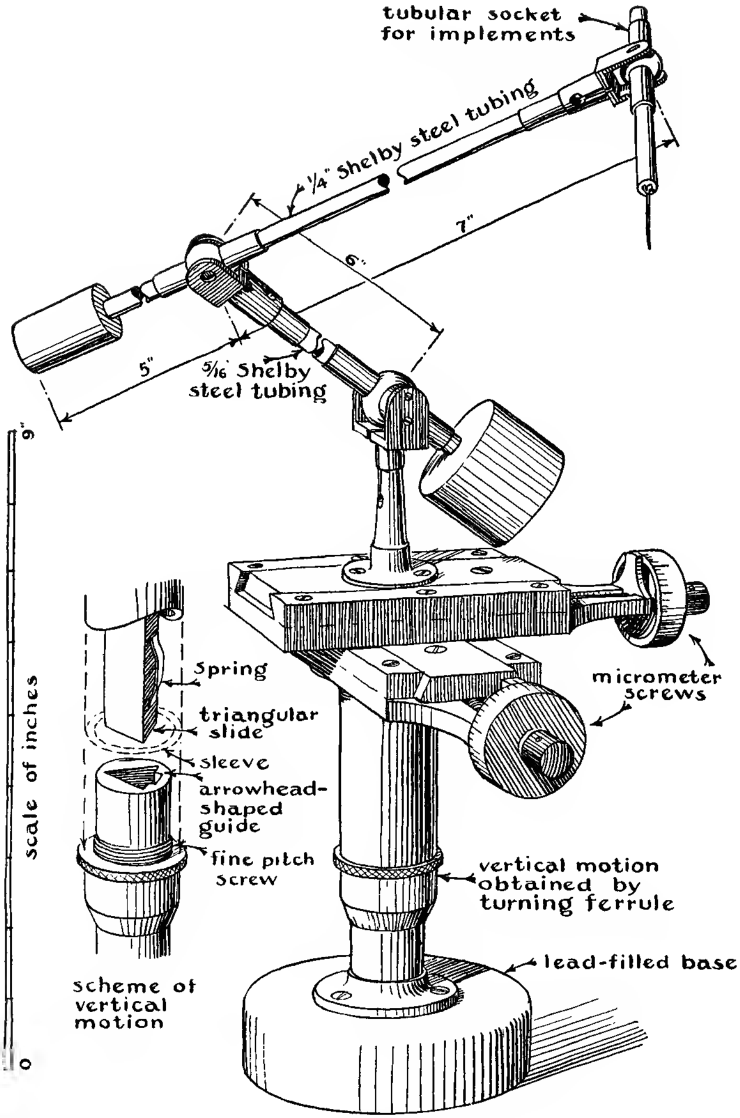


Fig. 10. Micromanipulator.

Although much of the simpler fiber work can be done with the unaided eye or with a magnifying glass, for fine work in which accuracy is important and ease of working is desired a binocular microscope with a magnification of 15 to 20 can be strongly recommended. Such a microscope not only gives stereoscopic vision but when used properly results in little, if any, eyestrain. A scale in one eyepiece allows

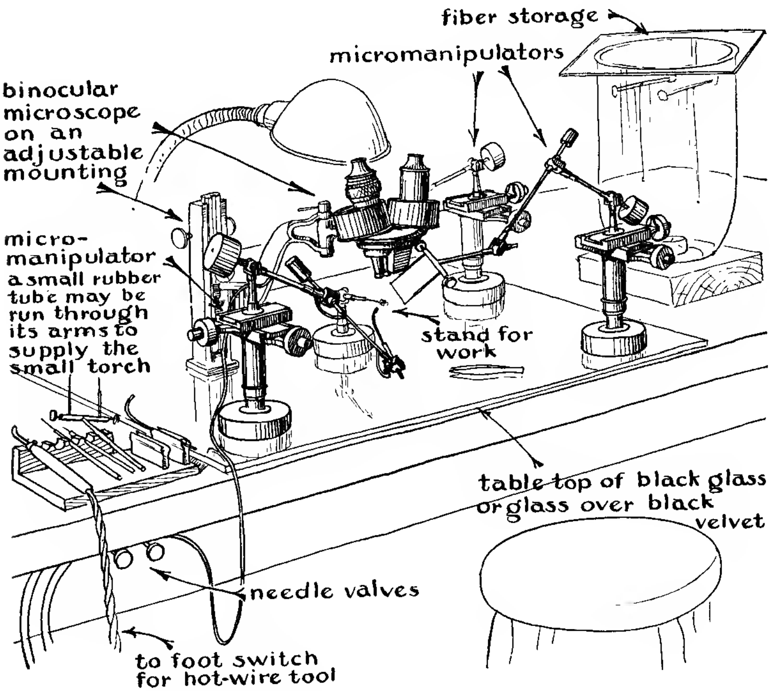


Fig. 11. Complete assembly for working quartz fibers.

measurements to be made. Lighting from several directions is desirable to provide proper illumination on the work in all positions.

A complete setup of the major equipment used by the writer in quartz fiber work is illustrated in Fig. 11. The black glass base permits the fine fiber to be seen easily by scattered light. When the actual outlines of large fibers

are to be seen, a piece of white paper is placed on the glass base and used as a background.

Making fibers. A convenient size of stock quartz rod is 3 to 4 mm in diameter. Smaller rod than this is apt to break when the larger fibers are being drawn and is not easily held in the hands. Larger rod becomes more difficult to melt.

The first step in making a fine fiber is to draw one from 50μ to 100μ in diameter. (See Fig. 12.) Two pieces of stock

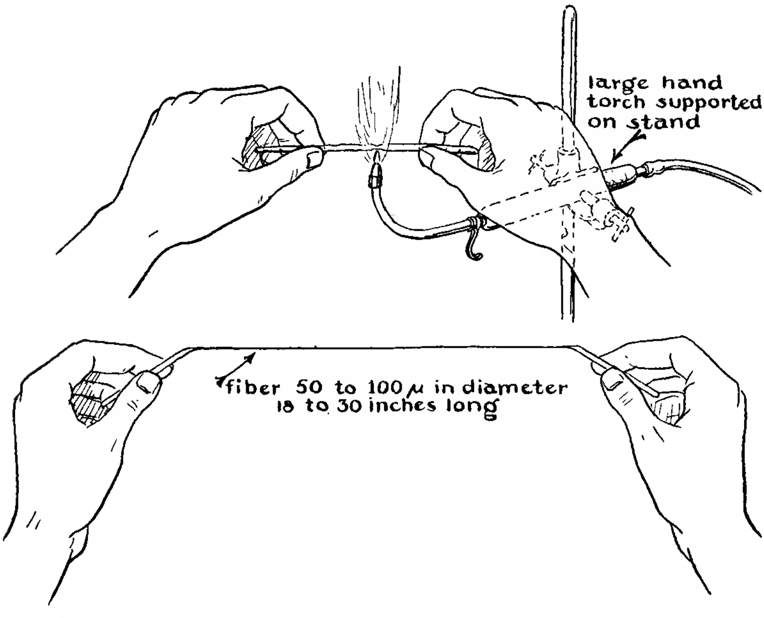


Fig. 12. The first step in making a small fiber is to draw a larger one. A very hot flame is used.

quartz of convenient length are held in the hands. The oxygen-gas flame is adjusted to maximum heat; that is, both the oxygen and gas are increased, especially the oxygen, until a hissing flame results, and the small cone just over the opening in the torch tip has shortened until its height is perhaps two or three times its width. The hottest portion of the flame is just above this small cone. The ends of the quartz rod are melted together and then pulled apart a short

distance, so that the connecting soft quartz is perhaps 1 mm in diameter. This portion, when held in the hottest part of the flame, will become quite soft. The quartz rods are then quickly removed from the flame, and at the same time the two pieces held in the hands are separated rapidly to a distance of several feet. The hotter the narrow section of quartz and the faster the drawing, the smaller will be the resulting fiber. Fibers down to 20μ can be drawn in this manner.

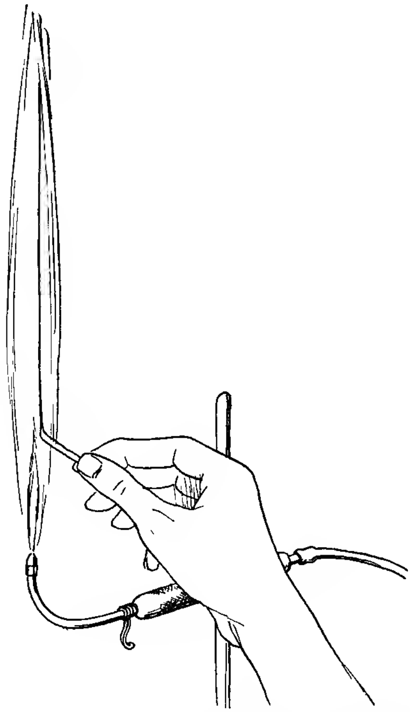


Fig. 13. The second step in making a small fiber is to blow out the larger fiber by holding it in a long, vertical, relatively cool flame.

To make a smaller fiber from the larger one, the procedure is as follows: Break the connecting fiber produced in the above drawing process so that a section of 8 to 10 inches is left on each piece of quartz stock. This section should be stiff enough to support itself in a vertical position. Now adjust the flame by turning the oxygen partially off, so that a steady flame about 15 to 20 inches long is produced. The cone above the tip will lengthen to several inches. Holding the quartz stock so that the attached fiber is vertical, move it into the vertical flame as illustrated in Fig. 13. The whole length of the fiber will glow uniformly. If the temperature of the flame and the size of the fiber are right, the fiber will gradually begin to lengthen, slowly at first and then more rapidly as it becomes smaller. Finally, the upper section of the original fiber will go quickly toward the ceiling.

As soon as this happens, the lower end should be removed from the flame. A careful examination will reveal a fine fiber joining the two ends of the original, perhaps 3 to 6 feet long. Sections of it can be seen in scattered light. Place a small tab on one part of the fine fiber with one hand while holding the stock quartz (to which the other end of the fiber is attached) in the other. The position of the intervening portion is now determined, so that other tabs can be stuck on and suitable lengths removed. Each end of each length will thus have a small tab attached. These fibers are then stored in a clean container in which the air is kept dry. (See Fig. 14.)

The size of the resulting small fiber will depend on a number of factors. Chief among these are the size of the original fiber, the temperature and size of the flame, and the time intervening between the disappearance of the top of the original fiber and the removal of the lower end. Some practice is necessary to secure fibers of a desired size. It will be found that fibers produced in the above manner are straight and of quite uniform diameter for some distance on each side of the center.

A few cautions are necessary if good fibers are to be had. The basis of all of these is cleanliness. Much of the dust on objects around a laboratory and floating in the air is inorganic. If a fiber is heated where a piece of dust has settled, the metallic salts form silicates and in general completely spoil the surface, and for that reason the fiber also, at the point of contact. It is a general rule that no part of a fiber which ultimately is to have any stress applied should ever touch anything except those materials which are softer than the quartz and will not react with it. This may seem to be a stringent requirement, but in reality the fiber can always be handled by its ends, which are eventually discarded.

If the original large fiber shows any bright spots when put into the flame, it should be discarded. In general, this is the best test for dust that can be applied. Dust will immediately show itself by causing a bright spot, and the fiber can be

discarded forthwith; if there is no dust on the fiber, it will not be harmed by heating. This test can be made with fibers from 10μ to 100μ with an ordinary Bunsen burner. For smaller ones the small torch using a pure gas flame should be used. In each case the fiber should be under some tension to keep it straight.

If the size of the fiber is to be measured with the microscope, it is usually sufficient to take a sample from each end and take the mean diameter. The sample is placed on a piece of glass, which in turn is placed on the microscope stage and viewed by transmitted light. To find the fiber in the microscope the following procedure is valuable in saving time: Have plenty of light passing through the optical system. Raise the objective until it is several times the working distance from the object. Remove the ocular. Move the glass on which the fiber is lying until, by looking down the microscope tube, the reduced image of the fiber is seen. Adjust the position of the fiber until its image appears approximately in the middle of the objective. Now move the objective down until the image begins to spread. When it appears to cover the objective completely, the object is near the focus, and on replacing the ocular, the image should be in the field of view.

After working with fibers for a while, one can judge their size by the amount of scattered light, the amount of weaving in the air, how much a fiber of a given length sags under its own weight, the radius of curvature when hung over a needle with a tab on one end, and so forth. These methods are good to from 20 to 50 per cent, except for fibers below 1μ to 2μ.

Another method for drawing fibers has been described by Boys.[7] It consists in pulling the two pieces of quartz apart very rapidly by means of a projected arrow. Long fibers down to 10μ of very uniform diameter can be produced in this fashion. The hotter the quartz and the faster the arrow is shot, the finer will be the fiber.

[7] *Ibid.*, Volume III, page 696.

The care and preservation of small fibers. When a fiber has its two ends marked with tabs, it should be hung in a clean, dry container. A crosspiece at the top of the container, on which are small pieces of soft wax or beeswax, serves as a hanger. The top tab is pressed into the wax, and the lower tab keeps the fiber from weaving around and touching things.

The container should be 10 to 12 inches deep, airtight, and preferably made from glass. It should be clean and contain a good drying agent—either phosphorous pentoxide or anhydrous potassium hydroxide. A convenient container is made from an inverted bell jar with a plate-glass top as shown in Fig. 14. Fibers deteriorate in moist atmospheres, but can be preserved for months with no change in breaking strength if kept clean and dry.

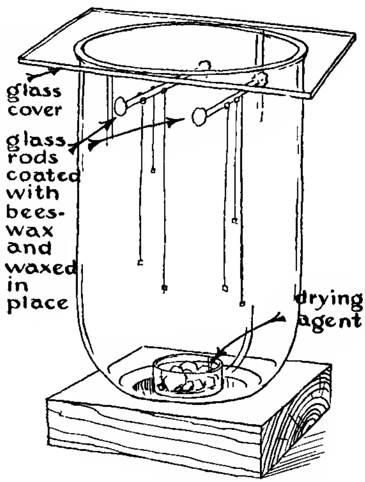


Fig. 14. Preserving quartz fibers.

Some useful techniques in fiber work. *Straightening.* Fibers from 10μ to 500μ can be quickly and easily straightened by hanging a weight on the lower end and running a Bunsen burner flame up and down the piece several times. The weight should be somewhat less than that necessary to elongate the fiber appreciably under the heat of the flame. A small Dennison tab is sufficient for fibers 10μ to 50μ and a $\frac{1}{2}$-inch tab for those between 50μ and 500μ. For fibers from 4μ to 10μ a small Dennison tab should be cut in two and the small torch burning pure gas used for heat.

Bending. Fibers from 40μ on up are best bent by hanging a weight such as a tab at one end, holding the fiber at the proper angle, and applying the heat locally with a small torch burning oxygen and gas. The piece between the

flame and the tab will fall to a vertical position as shown in Fig. 15.

Fibers between 1μ and 40μ are best bent over another piece of quartz. A weight such as part or all of a small tab or a small piece of wax bends the fiber over the larger piece of quartz (100μ or less). A pure gas flame applied with the small torch at the contact of the two fibers will bend the

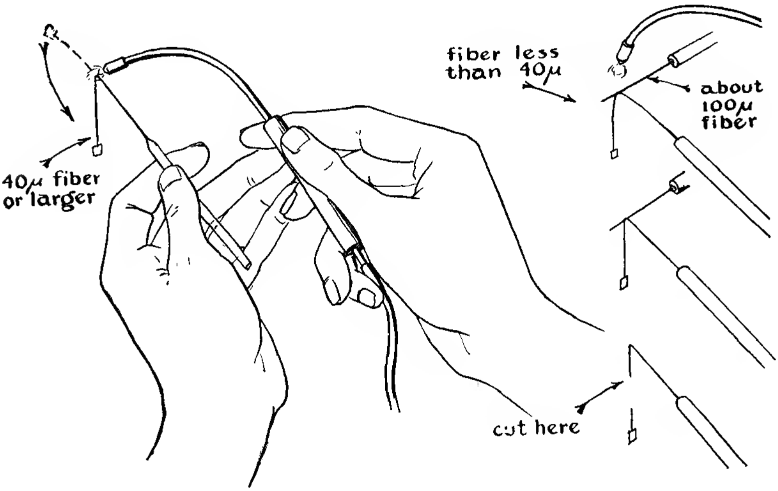


Fig. 15. Bending large and small fibers.

smaller one over the larger. The flame should not be applied longer than is necessary, or the two pieces of quartz are apt to stick together.

Drawing and shrinking. If one end of a fiber is attached to a screw-controlled sliding mechanism, such as the movable prong fork described earlier, a portion of it may be readily drawn down to any desired size by applying a flame with the small torch and gradually screwing out one prong.

Soft quartz has a high surface tension, and fibers tend to shrink when heated. The heating is done with the small torch. It is necessary to have a properly adjusted flame. A compromise must be made between a hot flame with swiftly rushing gases, which readily melts and blows the fibers

apart, and a cooler flame, which will not soften the quartz sufficiently. The ideal is reached when the tendency to blow away is overcome by the tendency to pull together due to surface tension. The fiber is heated in a slackened condition, and as the shrinkage proceeds it is fed by the movable prongs. A torch tip with a hole about 0.1 mm in diameter is perhaps the best. With some practice a fiber may be locally enlarged to many times its previous diameter. (See Fig. 16.)

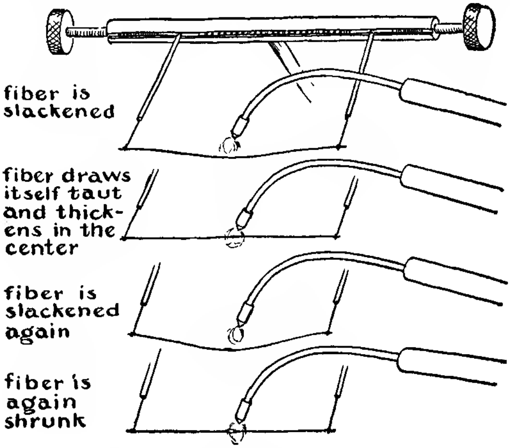


Fig. 16. Shrinking a small fiber.

Joining one fiber to another. When the above technique has been learned, the joining of two fibers crossing one another becomes simple. Each shrinks to the common junction, forming a joint which is stronger than any other portion. For this work it is necessary to use two of the forks with movable prongs, gradually feeding in the quartz as the joint grows in size.

Joining a fiber to a larger piece of quartz. If the larger piece is too large to melt locally with the small torch, a "teat" is put on at the proper place with a larger torch and then drawn down to a fine point. The fiber, mounted on the fork, is placed next to this teat, and heat is applied to the teat. Upon softening, the larger piece of quartz draws the small fiber in by surface tension. Straightening of the

fiber near the junction is done by heating with the small torch burning pure gas when the fiber is under a slight tension.

With care, fibers as small as 1μ in diameter can be melted to other fibers or larger pieces of quartz.

Drawing an oval fiber. The tip of each piece of the stock quartz is heated in the oxygen-gas flame so that only the

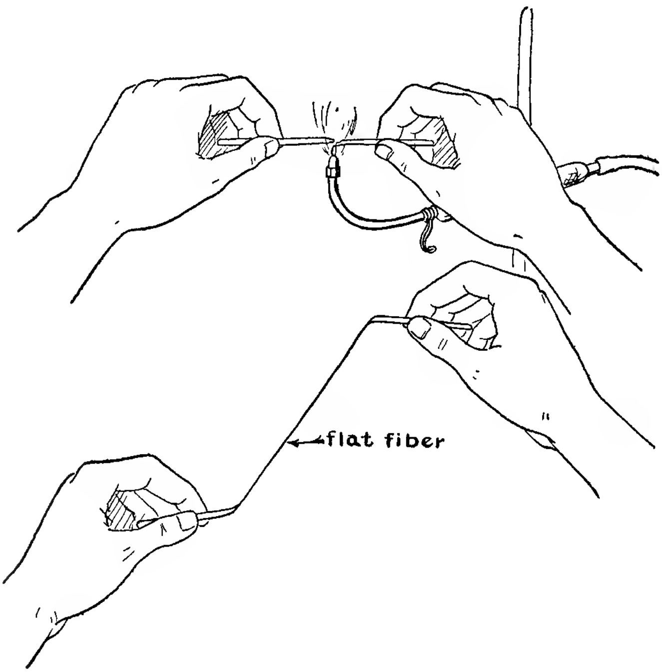


Fig. 17. Making a flat fiber.

very end becomes soft. With the axes of the two pieces held parallel, the ends are brought together and immediately separated at right angles to the axes of the stock quartz, and at the same time they are removed from the flame. (See Fig. 17.) Only flat fibers larger than 30μ to 40μ can be produced in this fashion. They are useful in vibration types of pressure gauges in which the motion is to be limited to one plane.

Drawing flat tubing. In some cases quartz is useful in making the Bourdon type of pressure gauge. If a long piece of flat tubing is made into a spiral and a mirror and scale are used to measure the change in angle, such a gauge becomes an accurate means of measuring moderate pressures. One way to produce long pieces of elliptically shaped thin-walled tubing is to use two large torches as cross-fires and to heat $\frac{1}{2}$- to $\frac{3}{4}$-inch quartz tubing without rotation. Heating should continue until the walls nearest the flame are quite soft. The tubing is removed from the flame and rapidly pulled to 3 or 4 feet. If heating has not been sufficient, the elongated occluded bubbles will cause the resultant tubing to be brittle. It is, in fact, a good procedure to work the heated section by alternately enlarging and contracting it with internal pressure before drawing. The oval tubing is bent into the desired shape with a moderately hot flame.

Making electrometer suspensions. Quartz fibers make ideal suspensions for electrometers. The most satisfactory way

Fig. 18. Design of quartz fiber support used in the Dolezalek and Compton electrometers. The whole is made from fused quartz, upon which is deposited a coating of metal, for example, gold or platinum.

of making the suspensions consists in joining the ends of the fiber to two larger pieces of quartz by melting them together with a small torch. In many cases these larger pieces are bent into small hooks, and then the whole is made conducting by evaporating or sputtering gold or some other metal on it as represented in Fig. 18. In cases in which hooks cannot be used, the larger quartz is left straight and is cemented into place with a hard wax such as DeKhotinsky's. Contact is made by attaching a fine wire to the quartz with hard wax before the fiber is coated with the metal. The wire is later soldered to the metal pieces of the electrometer.

The method of soldering the metal-coated fibers does not produce a suspension as permanent as with the methods described above. The gold is apt to amalgamate with the

solder and result in a poor contact between the main portion of the fiber and the solder.

Another method of fastening fibers to metal parts and at the same time making an electrical contact is to use colloidal graphite. A small drop is placed at the proper point, and in a short while the water will evaporate, leaving a strong conducting joint.

Quartz is very convenient for making various types of electroscopes. It is not only good for the moving parts but is used uncoated for insulation.[8]

Mounting cross hairs in optical instruments. Fibers made from quartz surpass any other material for cross hairs. Owing to the refraction of the light by the fiber, it appears black as seen in a bright field. Its essential smoothness, freedom from dust, uniformity of size, straightness, and the fact that it can be drawn to any desired diameter make it especially valuable.

The mounting is first prepared by melting hard wax onto it at the desired points. The fiber is mounted on a fork and

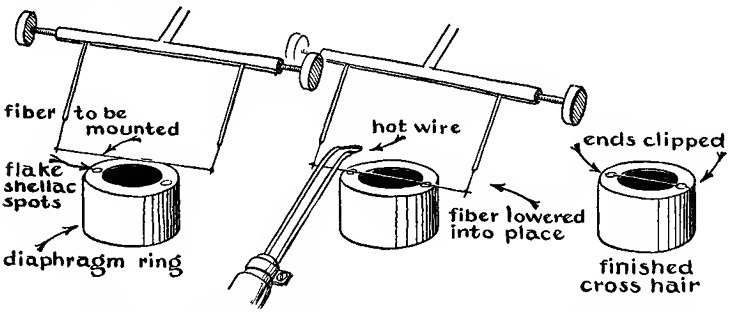


Fig. 19. Steps in mounting cross hairs for microscope and telescope eyepieces.

lowered into position. A hot wire brought near the wax where the stretched fiber rests will allow the fiber to sink in and become firmly attached. The various steps are illustrated in Fig. 19.

Torsion balance. For objects weighing less than 1 mg the torsion balance becomes very useful. It is not difficult

[8] See Chapter VI, "Electrometers and Electroscopes."

to make a balance having a sensitivity of 10^{-7} to 10^{-9} g/div. without the use of mirrors or microscopes. A simple calculation will show the size of fiber necessary for the specific requirements. The crossarm should be statically balanced. The amount of twist of the fiber is conveniently read from a divided head.

The balance may be calibrated by weighing on an analytical balance a long section of fine wire such as 40 B and S

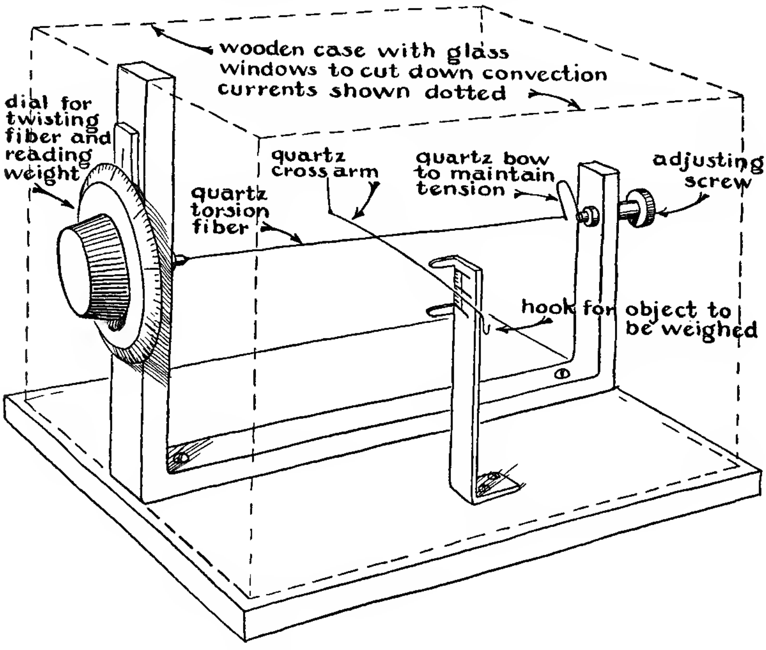


Fig. 20. Simple design of a quartz microbalance.

gauge copper, 2-mil nickel, or smaller if needed, and cutting from this piece samples of a given length. Usually ten samples will give a probable error of less than 1 per cent in the calibration. If the tension in the torsion fiber is kept constant with a quartz bow, it can be assumed with much accuracy that the twist is proportional to the weight. Since $\phi r/l$ is the surface strain, where r is the radius of the torsion fiber, ϕ the angle of twist in radians, and l the length twisted,

and since the maximum value of this is about 0.05, the maximum load which the balance can handle is easily computed. A simple design of such a torsion balance is shown in Fig. 20.

If all the joints are made of fused quartz, there need be no fear of a changing "zero," since the limit of elasticity coincides with the breaking point.

Other uses of quartz. Quartz rod or fiber is often used as a carrier of light—visible, ultraviolet, or infrared. Internal reflections keep the light inside the quartz and permit it to be led around corners, provided the corners are not too sharp.

In many cases in which accuracy in maintaining shape or position is important, quartz finds a use. All metals change their dimensions with time, especially when under strain. This change can be lessened by thorough annealing, which consists in subjecting the metal alternately to temperatures above and below room temperature. In extreme cases this treatment may take days or weeks. Annealed fused quartz does not suffer from changes in dimensions, since the flow under strain is less than 10^{-3} of that for metals.

Fused quartz is finding increasing uses in lamps of various kinds in which the transmission of ultraviolet light is important. For the same reason many photoelectric cells are made from quartz.

Although the above does not pretend to be an exhaustive list of the uses to which fused silica can be put, it is hoped that the reader will gain some idea of the usefulness of this material.

CHAPTER VI

Electrometers and Electroscopes

BY

H. V. Neher

Definitions. It is not always clear just what distinguishes an electrometer from an electroscope, and there seems to be some confusion in the literature. For purposes of this discussion the following distinction will be made: An electroscope is an electrostatic measuring device in which only one potential difference is needed for its operation. Electrometers, on the other hand, need auxiliary potentials for their operation. The familiar gold-leaf electroscope and the quadrant electrometer are respective examples.

General theory.[1] Expressed in terms of Maxwell's coefficients, the electrostatic energy of any system of conductors at potentials $V_1, V_2, \ldots V_n$ is given by[2]

$$W = \tfrac{1}{2}(c_{11}V_1{}^2 + 2c_{12}V_1V_2 + \ldots) = \tfrac{1}{2}\Sigma QV, \tag{1}$$

where the coefficients of capacity, c_{11}, c_{12}, c_{13}, and so forth, are given by

$$\left.\begin{aligned} Q_1 &= c_{11}V_1 + c_{12}V_2 + \ldots c_{1n}V_n, \\ &\vdots \\ Q_n &= c_{n1}V_1 + c_{n2}V_2 + \ldots c_{nn}V_n, \end{aligned}\right\} \tag{2}$$

the Q's being the charges on the conductors. The coefficients have the properties that $c_{ij} = c_{ji}$. c_{11} is the charge which is on conductor 1 when all the other bodies are grounded and

[1] This treatment follows, in general, that given by Hoffmann, G., in *Handbuch der Exp. Physik*, X, 42 (1928). Wein, W., and Harms, F., editors; Leipzig.

[2] Jeans, J. H., *Mathematical Theory of Electricity and Magnetism*, Fifth Edition, page 95. New York: The Macmillan Company.

1 has a potential of unity. Similarly c_{12} is the charge induced on 1 when all the other bodies are grounded and unit potential is placed on 2.

If the c's are functions of a coördinate ξ and the V's are kept constant, then the force or torque tending to increase ξ is

$$\frac{\partial W}{\partial \xi} = \frac{1}{2}\left(\frac{\partial c_{11}}{\partial \xi}V_1^2 + 2\frac{\partial c_{12}}{\partial \xi}V_1V_2 + \cdots\right). \tag{3}$$

In all instruments this electrical force or torque is balanced by some restoring force. If we know how the c's and the restoring force depend on ξ, then with the help of Eq. 3 we can solve for the voltage sensitivity.

Since most electroscopes and electrometers are used to measure electric charge, it is the charge sensitivity in which we are interested, although the voltage sensitivity is the more easily measured.

Referring back to Eq. 2, let i be the moving system. The charge sensitivity, S_Q, is given by

$$\frac{1}{S_Q} = \frac{\partial Q_i}{\partial \xi} = c_{i1}\frac{\partial V_1}{\partial \xi} + V_1\frac{\partial c_{i1}}{\partial \xi} + \cdots, \tag{4}$$

since both the c's and the V's are, in general, each functions of the coördinate.

Applications to electroscopes. The above theory when applied to electroscopes becomes very simple. In this instance we have but two conductors, usually one completely surrounding the other. Let the case be grounded. Then Eq. 1 becomes merely $W = \frac{1}{2}cV^2$, where c is the capacity of the electroscope system to the case. c must be a function of the displacement and in most instances can be considered a linear function, that is, $c = c_0 + b\xi$. For this case Eq. 3 becomes $\partial W/\partial\xi = \frac{1}{2}bV^2$. If this is balanced by a force proportional to the displacement, then $k\xi = \frac{1}{2}bV^2$, and the voltage sensitivity is

$$S_V = \frac{1}{\dfrac{\partial V}{\partial \xi}} = \frac{bV}{k}. \tag{5}$$

From Eq. 4, the charge sensitivity, S_Q, is given by

$$\frac{1}{S_Q} = c\frac{\partial V}{\partial \xi} + V\frac{\partial c}{\partial \xi}. \tag{6}$$

Now $\partial V/\partial \xi$ is given by Eq. 5, and $\partial c/\partial \xi = b$ if c is a linear function of ξ. Therefore

$$S_Q = \frac{bV}{ck + V^2b^2}. \tag{7}$$

For most electroscopes, b^2V^2 is small compared with ck, so that we can usually write

$$S_Q = \frac{bV}{ck} = \frac{S_V}{c}. \tag{8}$$

This last relationship between the voltage and charge sensitivities is the usual assumption made when working with electroscopes.

However, b^2V^2 need not be small compared with ck, and it is interesting to see what follows in such a case. It will be seen that Eq. 7 has a maximum value when $V_0^2b^2 = ck$, and under these conditions

$$(S_Q)_{\text{max.}} = \frac{1}{2}(ck)^{-1/2} = \frac{1}{2V_0b}.$$

The effective capacity has increased to

$$c_{\text{eff.}} = \frac{\dfrac{\partial Q}{\partial \xi}}{\dfrac{\partial V}{\partial \xi}} = 2c.$$

Any further increase in the voltage sensitivity results in a more rapidly increasing capacity and a decrease in charge sensitivity.

These conditions more aptly apply to electrometers and will be discussed in that connection in the following section.

Applications to electrometers. All electrometers can be considered as made from three conductors, two of which are stationary and usually similar, while the third is movable. All three are connected electrically to the outside of the instrument. We shall assume in the following discussion that

the charge or potential to be measured is applied to the movable system, while the two stationary parts are maintained at equal and opposite potentials. This arrangement is not necessary, and in general the following discussion holds equally well for the case when the charge or potential to be measured is applied to a stationary part and the moving system is kept at the high potential. It is further assumed that the electrical and mechanical zeros of the instrument coincide. This last condition is fulfilled if, while the movable system is grounded with equal and opposite potentials applied to the stationary parts, no deflection takes place.

Of the twenty-seven terms in Eq. 3, twenty-five are small or zero, as compared with the remaining two under the above conditions. If the moving part is symmetrical with respect to the stationary parts, then these two terms are equal, and Eq. 3 becomes

$$\frac{\partial W}{\partial \xi} = V_1 V_3 \frac{\partial c_{13}}{\partial \xi},$$

where c_{13} is the capacity between the moving system and one of the stationary parts, which is at a potential V_1, while V_3 is the potential of the moving system.

Case I. In general, c_{13} will be a complicated function of ξ. This is especially true in the case of most string electrometers, but with the Hoffmann and Dolezalek the dependence of the capacity on the displacement is approximately linear. For these instruments $c_{13} = c_{13}^0 + b\theta$, and the torque becomes

$$L = V_1 V_3 b. \tag{9}$$

In equilibrium, $L = k\theta$, where k is the torsion constant of the suspension. It will be noticed that Eq. 9 is symmetrical in V_1 and V_3, so that the sensitivity is the same whether the stationary or the moving parts are at the fixed potential. Assuming that the stationary parts are kept at a fixed potential, the voltage sensitivity is

$$S_V = \frac{V_1 b}{k}. \tag{10}$$

The charge on the moving system, 3, becomes

$$Q_3 = c_{13}V_1 + c_{23}V_2 + c_{33}V_3.$$

Now the moving system is connected to a suspension which in turn is connected to an external capacity. Let the sum of these two capacities be denoted by c_e. If a charge q is placed on the system, then $Q_3 = q - V_3c_e$, and we have

$$q = c_{13}V_1 + c_{23}V_2 + (c_e + c_{33})V_3$$

and

$$\frac{1}{S_q} = \frac{\partial q}{\partial\theta} = c_{13}\frac{\partial V_1}{\partial\theta} + V_1\frac{\partial c_{13}}{\partial\theta} + c_{23}\frac{\partial V_2}{\partial\theta} + V_2\frac{\partial c_{23}}{\partial\theta} + (c_e + c_{33})\frac{\partial V_3}{\partial\theta} + V_3\frac{\partial c_{33}}{\partial\theta}.$$

Now c_{33}, to the desired approximation, is not dependent on θ, and $\partial c_{13}/\partial\theta = -\partial c_{23}/\partial\theta = b$. Also $V_2 = -V_1$ and $\partial V_1/\partial\theta = \partial V_2/\partial\theta = 0$. The charge sensitivity becomes

$$S_q = \frac{V_1b}{2V_1{}^2b^2 + (c_e + c_{33})k}.$$

$(c_e + c_{33})$ may be lumped into one quantity c, which is the electrostatic capacity of the electrometer and external system when the stationary pieces are grounded. Hence

$$S_q = \frac{V_1b}{2V_1{}^2b^2 + ck}. \qquad \textbf{(11)}$$

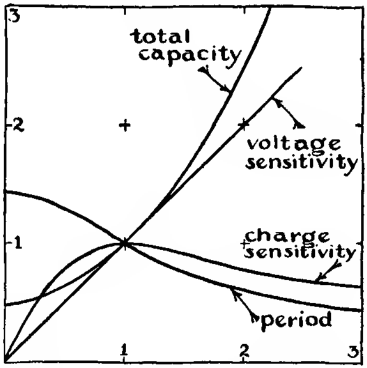


Fig. 1. The total capacity, voltage sensitivity, charge sensitivity, and period (ordinates) of an ideal electrometer in terms of their values at the optimum value of the plate potential. The plate potential is measured along the abscissa, and its optimum value is taken as unity. See W. W. Hansen, *R.S.I.*, 7, 182 (1936).

This has a maximum value at $V_0 = (1/b)(ck/2)^{1/2}$, and this is the value of V_1 which should, if possible, be used on the binants or the quadrants, as the case may be, if high charge sensitivity is wanted. This makes $(S_q)_{\text{max.}} = \frac{1}{2}(2ck)^{-1/2} = 1/(4V_0b)$. Any further increase in V_1 will increase the voltage sensitivity but will decrease the charge sensitivity. The behavior of the total capacity, voltage sensitivity, charge

sensitivity, and period, as the auxiliary potentials are changed, is shown in Fig. 1.

Experimentally, the proper value of V_1 is easily determined, as will be seen from what follows. The effective capacity is

$$c_{\text{eff.}} = \frac{\partial Q}{\partial \theta} \cdot \frac{1}{\dfrac{\partial V}{\partial \theta}} = 2c$$

at the optimum value of V_1. The procedure is as follows: Determine the electrostatic capacity of the suspension and moving system, together with any permanently connected capacity such as an ion chamber. Call this total c. Compare the deflection of the electrometer when a potential V is applied with that obtained when the same potential is applied through a known capacity c_s as shown in Fig. 2. Then when the ratio of the deflections in the two cases is

$$\frac{\theta_1}{\theta_2} = \frac{2c + c_s}{c_s},$$

V_1 has the proper value.

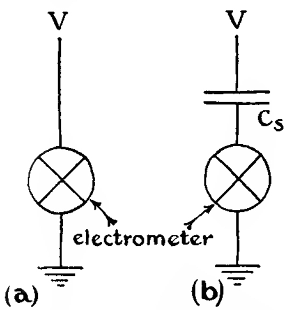


Fig. 2. A method for determining the effective capacity of an electrometer in terms of a standard capacity, c_s.

The period may also be computed. When there is no net charge on the electrometer and when potentials are on the binants or quadrants, let the system be deflected through an angle θ by some external means and then allowed to vibrate. By Eq. 11,

$$2V_1b + c\frac{\partial V_3}{\partial \theta} = 0,$$

and

$$V_3 = -\frac{2V_1b}{c}\theta.$$

The electrical torque from Eq. 9 is therefore

$$L = -\frac{2V_1^2b^2}{c}\theta.$$

Now the resultant torque is

$$-\frac{2V_1^2b^2\theta}{c} - k\theta,$$

the equation of motion becomes

$$I\frac{d^2\theta}{dt^2} = -\left(\frac{2V_1^2b^2}{c} + k\right)\theta,$$

and the period is

$$T = 2\pi\sqrt{\frac{I}{\frac{2V_1^2b^2}{c} + k}},$$

where I is the moment of inertia of the moving system. Now at the optimum value of V_1, $2V_1^2b^2 = ck$, and hence the corresponding period is

$$T = 2\pi\sqrt{\frac{I}{2k}}. \tag{12}$$

In other words the period has become 40 per cent less than when no potentials are applied. The maximum charge sensitivity in terms of the period, capacity, and moment of inertia of the system becomes

$$(S_q)_{\text{max.}} = \frac{T}{2\pi}(cI)^{-1/2}. \tag{13}$$

Case II. If the coefficients c_{13} and c_{23} are quadratic functions of the displacement, that is, if

$$c_{13} = c_{13}^0 + b\theta + g\theta^2,$$

the values of the voltage and charge sensitivities are as follows:

$$S_V = \frac{V_1b}{k - 2gV_1V_3},$$

or

$$S_V = \frac{V_1b}{k}\left(1 + \frac{2g\theta}{b}\right),$$

and

$$S_q = \frac{V_1(b + 2g\theta)}{2V_1^2(b + 2g\theta)^2 + ck}.$$

The optimum value of V_1 is given by

$$V_0 = \frac{1}{b + 2g\theta}\left(\frac{ck}{2}\right)^{1/2}$$

and

$$(S_q)_{\text{max.}} = \tfrac{1}{2}(2ck)^{-1/2}.$$

This last is just what was obtained when the dependence of the capacity between the moving and stationary parts was a linear function of the displacement.

The effective capacity at the maximum charge sensitivity is the same as in the simpler case, namely, twice the pure electrostatic capacity.

The total torque may be written as

$$L = -\left(k + \frac{2V_1{}^2b^2}{c}\right)\theta - \frac{6V_1{}^2bg\theta^2}{c}.$$

If g is positive, then the electrometer has what is known as positive control, while if g is negative, it has negative control. In the latter case the net torque may become zero at some point of the deflection, in which case the instrument becomes unstable. This frequently occurs when the sensitivity is high and is especially true with string electrometers, limiting the useful range to deflections near the midpoint. The period becomes longer if g is negative and will become longer the greater the amplitude of vibration.

It will be seen from the characteristics of the instrument in Case II that they are not so desirable as those in Case I, since they depend on the amount of displacement. However, there may be other advantages which make instruments of the second type more desirable, such as portability, ease of operation, and so forth. It should be borne in mind also that the above theory contains many simplifying assumptions, and the actual behavior of the instrument in some cases may be quite different. The chief differences are due to (1) a more complicated dependence of the capacity, between the stationary and moving parts, on the displacement and (2) air damping of the moving system. It is important to realize that where electrical charge is to be

measured, there is an optimum value of the potential applied to the stationary parts for which the charge sensitivity has either an optimum or a maximum value, and that there is experimentally an easy way to test for such a condition.

Some types of electroscopes. The familiar gold-leaf electroscope is made either with a vertical stationary metal piece and a single strip of gold leaf fastened near the top, or with two gold leaves mutually repelling each other as shown in Fig. 3. The lead-in is insulated from the metal box with an amber or sulphur bushing. The capacity will be from 3 to 5 cm and the potential necessary to give a 45° deflection will be from 300 to 500 volts. When the leaf is observed with a microscope or a telescope, it becomes a quantitative instrument and will serve many purposes where high charge sensitivity is not important. The technique of mounting the gold leaves will be discussed at the end of this chapter.

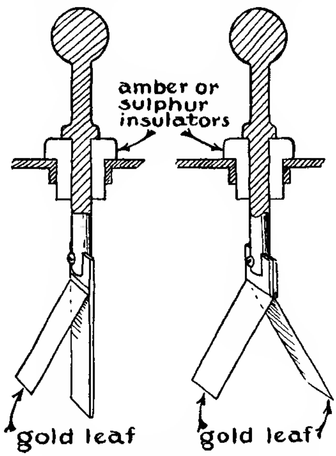


Fig. 3. Two types of gold-leaf electroscopes.

The Wilson tilted electroscope, designed by C. T. R. Wilson[3] and G. W. C. Kaye,[4] is a hybrid of the electroscope and the electrometer. The narrow gold leaf in Fig. 4(a) hangs normally in a downward position, and is observed by means of a microscope with a micrometer ocular. A potential of about 200 volts is applied to the plate. This plate is adjustable; that is, it can be moved in or out along the axis of its support. The proximity of the plate and the

[3] Wilson, C. T. R., *Cambridge Phil. Soc., Proc.*, *12*, 135 (1903).
[4] Kaye, G. W. C., *Phys. Soc., Proc.*, *23*, 209 (1911).
This instrument is made by Cambridge Scientific Instrument Company, Ltd., Cambridge, England.

potential applied to it give an electrostatic control which tends to neutralize the effect of gravity on the leaf.

Three cases in general may be cited for the voltage sensitivity as shown in Fig. 4(b): Case I, where there is little electrostatic control and the voltage sensitivity is linear over the entire scale; Case II, where the leaf is stable over the whole range but the electrostatic control is almost sufficient to neutralize the effect of gravity over part of the range; Case III, where there is an unstable region and consequently two "zeros." Case II is the most useful, and if deflections are taken over the same regions of the scale, there is no trouble about nonlinearity.

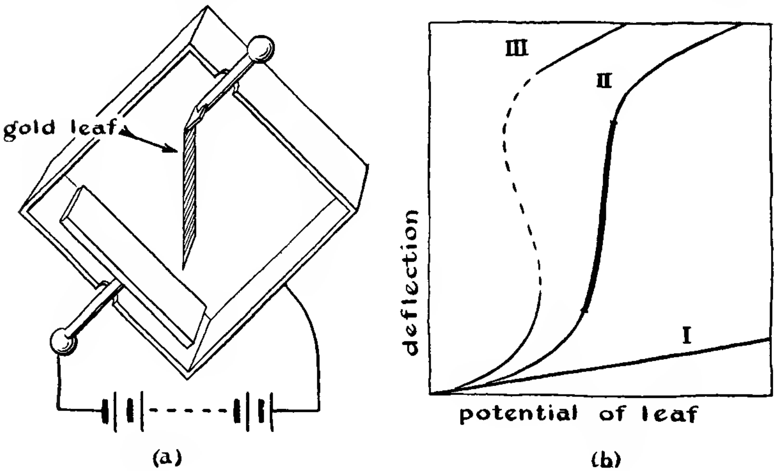


Fig. 4. Schematic diagram of the Wilson tilted electrometer and some typical sensitivity curves.

The Wilson tilted electroscope, while it may find a use in some types of work, has been largely displaced by more modern instruments, such as quadrant and string electrometers.

The Wülf bifilar electroscope[5] has frequently been used in cosmic-ray work. It is well suited for a portable instru-

[5] This instrument can be obtained from E. Leybold's Nachfolger A. G. Köln-Bayental, Bonner Strasse 500, Germany.

ment but must be read in a fixed position. As is the case with most electroscopes, not only the reading but also the calibration is affected by tilting the instrument. It is usually enclosed in an airtight ionization chamber, in which the gas pressure is often increased to increase the number of ions formed by a given radiation. The charge is renewed on the electroscope either by a mechanical arm working through an airtight bushing in the wall or, what is better, by an internal arm operated by an electromagnet.

The construction of the electroscope proper is shown in Fig. 5. A clean quartz rod is cemented into the metal piece which holds a short 0.5-mm rod by means of a set-screw. The small rod is flattened at the lower end. Two metal-coated straight quartz fibers from 5 to 10 cm long and from 10μ to 20μ in diameter are cemented or soldered (with Wood's metal) to the flattened piece. The lower ends of the two fibers are cemented side by side to an insulating quartz bow made from 10μ to 20μ fiber. It is essential that the fibers, when uncharged, hang parallel to each other. Means of straightening quartz fiber will be found in Chapter V. If shellac is used as a cement, there will be sufficient conductivity from the metal to the fibers. The potential of 200 to 400 volts is applied to the upper metal support. If the fibers are 20μ in diameter and 8 cm long, a spread of 3 mm will be produced by about 300 volts. The capacity will be in the neighborhood of 1 cm.

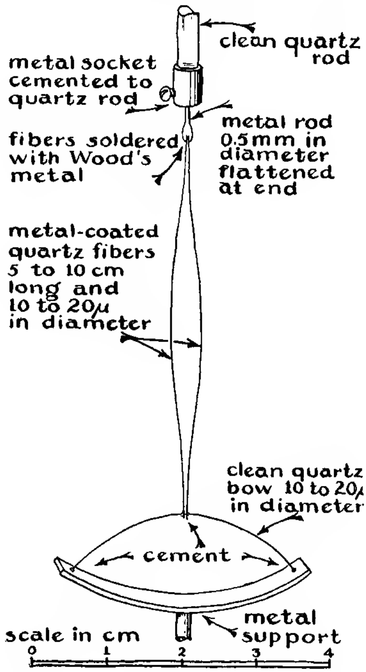


Fig. 5. Wülf bifilar electroscope.

The plane of motion of the fibers should be perpendicular to the optical axis of the microscope, the necessary adjustment being made by rotating the piece held by the setscrew.

It is possible to increase the sensitivity of the Wülf electroscope either by increasing the magnification of the microscope or by decreasing the diameter of the fibers. However, this is limited by the fact that the collecting potential for the ions should not drop too low, depending on the nature of the gas and its pressure. It is customary to have a collecting potential of not less than 100 volts.

From Eq. 8 the charge sensitivity is

$$S_Q = \frac{S_V}{c},$$

and if n is the average number of ions per second collected from each cubic centimeter of the gas, then

$$n = \frac{c}{ev} S_V \frac{d\xi}{dt},$$

where v is the volume of the ion chamber and e is the charge on the ions. The capacity c will vary with the spread of the fibers. The determination of c for different displacements amounts to the determination of b in $c = c_0 + b\xi$.

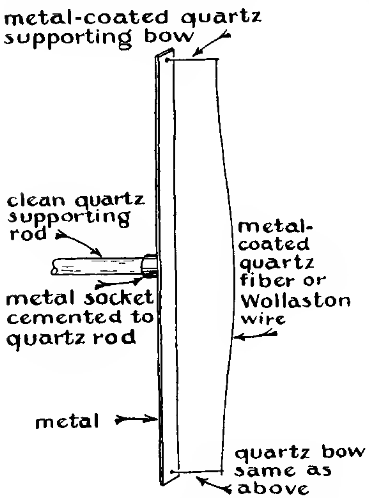


Fig. 6. Regener's electroscope.

Regener's electroscope is a single-fiber type shown in Fig. 6. The conducting quartz fiber or Wollaston wire is mounted near a metal piece and is held taut by a fine bow. The whole is supported by a quartz insulator, and the charge is renewed in a way similar to that used with the Wülf type.

Lauritsen has used a small quartz-fiber electroscope with much success not only in small pocket dose-meters for

X-ray work but also in measuring radiations found in nuclear investigations. Its outstanding feature is its simplicity. A wire is flattened at one end and bent over at right angles. A 5μ (0.005-mm) metal-coated quartz fiber about 6 mm long is cemented to this flat piece with shellac or colloidal graphite, making an angle with the wire support as shown in Fig. 7. A short piece of the same size fiber is cemented to the end of the longer fiber, at right angles to the plane of the wire and to the first fiber. This added piece is to form an index for viewing with a microscope. The wire support is mounted in an amber insulator, which in turn is mounted on the end

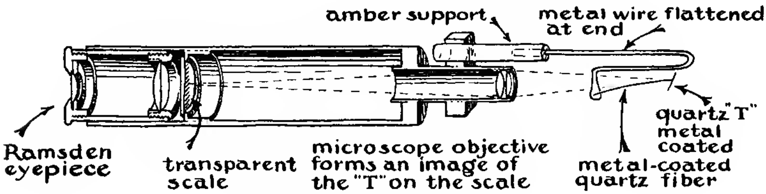


Fig. 7. Lauritsen's electroscope.

of the microscope. When the electroscope is used inside an ionization chamber, contact is made by a movable arm to the base of the metal support.

In order to obtain reliable readings on cosmic rays in airplanes, a torsion type of electroscope was developed in 1932. It was necessary to have a self-recording instrument of high sensitivity, the readings of which would not be affected by tilt or vibration of the plane. As far as tilt is concerned, this effect on the readings can be reduced to less than 0.001 of the total deflection for a tilt of 90°. As for vibration, satisfactory readings have been obtained with the electroscope mounted within 3 feet of the engine in a pursuit airplane.

A drawing of the electroscope is reproduced in Fig. 8. It is made entirely of fused quartz. The torsion fiber is stretched until its length is increased about 1 per cent. The crossarm is bent at right angles at one end and, in case high magnification is used, it is drawn down to a convenient size. A short bit of fiber serves as a fiducial mark. The

shapes of the stationary parts combine to give a linear scale over most of the range of discharge. A piece of platinum cemented to the quartz with a polymerizing cement is the point at which a new charge is placed on the system. With a very small oxygen-gas flame all joints are fused together so that the whole system becomes essentially one piece of

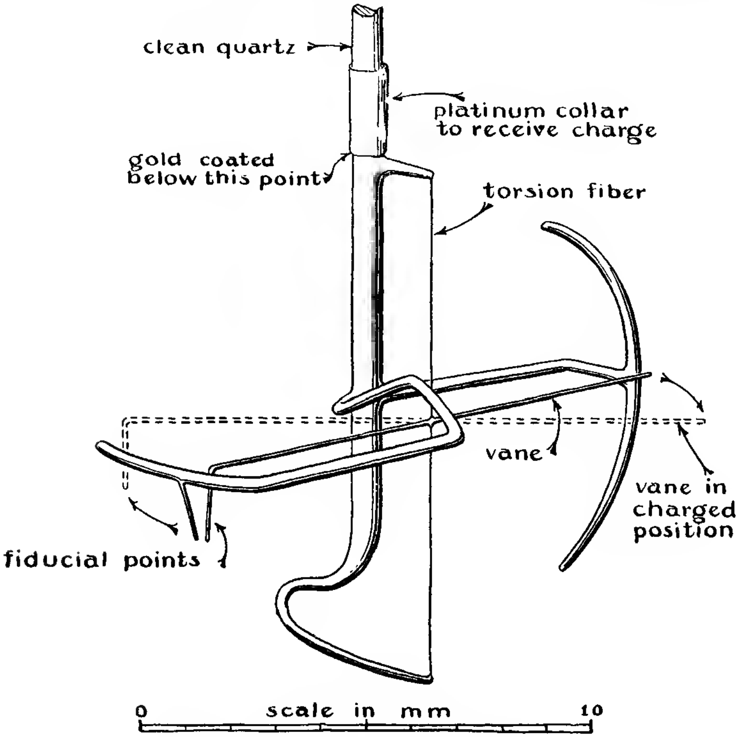


Fig. 8. Torsion type of electroscope.

quartz. The system from the platinum down is covered with a conducting layer of gold. The vane is balanced by cutting off one end. For many applications this balancing need not be done with great care and, in fact, becomes rather delicate if a very fine torsion fiber is used. If too much is cut off, mass can be added by applying some thin gold china paint[6] and heating it with a hot wire.

[6] See Chapter V.

In general it will be necessary to put a permanent twist in the torsion fiber. This can be done by forcing the vane beyond the stop through the desired angle, relieving the tension by pushing on the bow at the bottom, and heating the fiber at each end with a small pure gas flame. This will soften the quartz just enough. The twist, of course, must be put in before the system is covered with its conducting coating of metal. The following illustration gives some idea of how much twist is needed: With a torsion fiber 5μ in diameter and 12 mm long and a crossarm or vane 18 mm long, if a 30° twist is put in the fiber, the deflection will begin at about 200 volts and the sensitivity will be about 2×10^{-3} radian/volt. The electrostatic capacity will be about 0.5 cm and the charge sensitivity about 1.2 radians/statcoulomb.

Assuming a rigidity modulus of 5×10^{11} dynes cm^{-2}, the torsion constant comes out 1×10^{-2} dyne cm radian^{-1} under the above specifications, and b (see Eq. 5) has a value of

$$b = \frac{S_V k}{V} = 0.6 \times 10^{-2} \text{ cm radian}^{-1}$$

with $V = 1$ statvolt. Since b is a geometrical quantity, it will not depend on the size of the torsion fiber. The above relation may be used to get an approximation to the sensitivity for other values of the torsion constant k.

If a very fine torsion fiber is used, in order to keep the collecting voltage up it may be necessary to twist the torsion fiber around one or more times. If the crossarm is not larger than 20μ in diameter, this can be done manually after the conducting coat has been put on by using a needle and forcing the ends through, between the torsion fiber and the main quartz support.

Some types of electrometers. The Dolezalek quadrant electrometer[7] is perhaps the most common type and the most useful. The general plan of the instrument is shown in

[7] This instrument is made by many firms, including the Cambridge Scientific Instrument Company, Ltd., Cambridge, England, the Cambridge and Paul Instrument Company, Ltd., and E. Leybold's Nachfolger A. G. Köln-Bayental, Bonner Strasse 500, Germany.

Fig. 9. It consists of a cylindrical box, or "pillbox," divided into four equal and insulated quadrants. Opposite quadrants are connected together. There are two ways of using quadrant electrometers. One is to keep the needle at the high potential with respect to ground and apply the

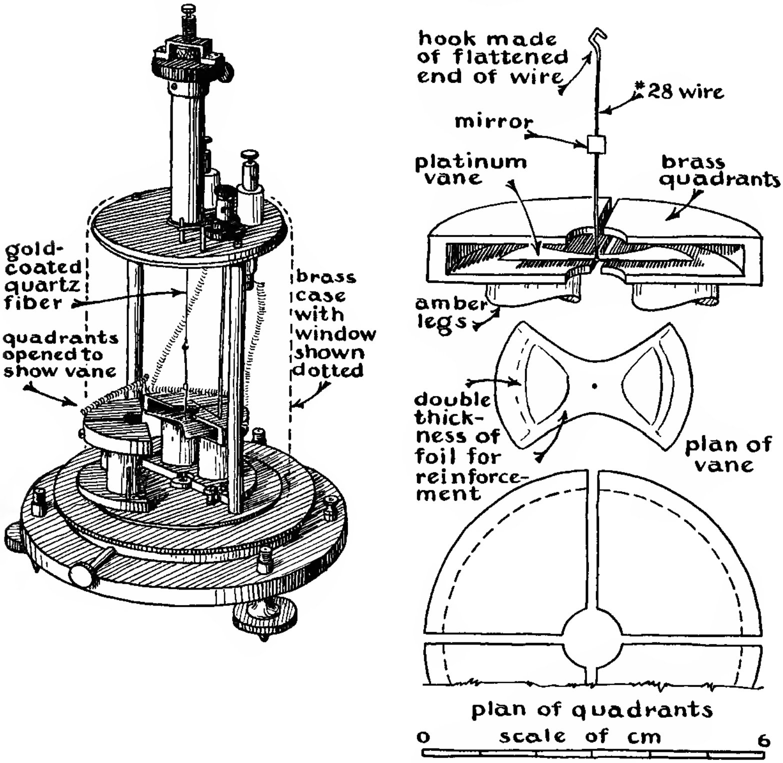


Fig. 9. Dolezalek quadrant electrometer.

charge to be measured to one pair of quadrants while the other pair is grounded. The other way is to maintain one pair of quadrants at the potential $+V$ and the other at $-V$ and place the charge to be measured on the needle. The first method is illustrated in Fig. 10(a). V will usually be from 50 to 150 volts, depending on the desired sensitivity.

For the second case the battery connections can be those shown in Fig. 10(b), where the main batteries furnish only a

potential and slight adjustments are made by a potentiometer as shown. Or the main batteries may be placed across the high resistances R and R, and adjustments are made with the potentiometer R', as represented in Fig. 10(c). The former circuit has the advantage that the life of the high-voltage batteries is essentially their shelf life, while the chief advantage of the second is that $|+V_1|$ always equals $|-V_1|$ and that the mechanical and electrical zeros remain together once they are made to coincide. However, modern "B" batteries maintain a remarkably constant potential at no current over long periods of time and have a very low temperature coefficient, so that in many cases the first circuit can be used.

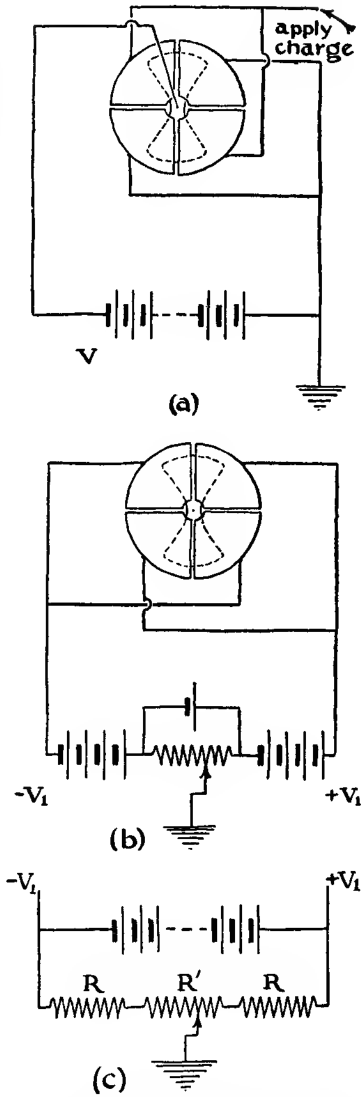


Fig. 10. Methods of applying the fixed potentials to the quadrant electrometer.

An approximation can be made to the value b for the Dolezalek electrometer in terms of the geometry of the instrument. It will be seen that the vane is of such shape that the capacity between the vane and the box, as a deflection takes place, varies linearly with the change of angle. Let θ be the deflection, R the radius of the vane, h the distance of the vane from one side of the box, and d the depth of the box.

Then b is the increase of capacity between the vane and the conductor into which it moves per unit of angle, or

$$b = \frac{R^2 d}{8\pi h(d - h)}.$$

Since there is an equal and opposite vane on the other side, the total electrical torque, by Eq. 9, is

$$L = \frac{V_1 V_3 R^2 d}{4\pi h(d - h)},$$

which at equilibrium is equal to $k\theta$. The voltage sensitivity is then

$$S_V = \frac{V_1 R^2 d}{4\pi h k(d - h)}, \tag{14}$$

and the charge sensitivity is

$$S_q = \frac{2\pi V_1 R^2 h d(d - h)}{(V_1 R^2 d)^2 + 8\pi^2 c k h^2 (d - h)^2}. \tag{15}$$

At the optimum value of V_1,

$$V_0 = \frac{4\pi h(d - h)}{R^2 d}\left(\frac{ck}{2}\right)^{1/2}$$

and the maximum charge sensitivity becomes

$$(S_q)_{\text{max.}} = \tfrac{1}{2}(2ck)^{-1/2}.$$

The effective capacity at this sensitivity is, of course, $2c$, where c is the total electrostatic capacity on which the charge q is placed.

Eqs. 14 and 15 predict a constant voltage and charge sensitivity for given values of the potential on the quadrants or on the needle and for given geometrical conditions. Actually, however, this is not the case, for it will be found that as the potential on the quadrants or on the needle, as the case may be, is increased, the period gradually lengthens, and a value is finally reached at which the vane becomes unstable at a certain point of the scale. This behavior is due to the occurrence of nonlinear terms in the expression for the capacity between the vane and the quadrants. By careful adjustment the importance of these terms can be diminished but never eliminated.

In setting up the Dolezalek electrometer, the vane should not be too close to either the top or the bottom of the box, since small variations due to changes in temperature and so forth will change the characteristics. Also, irregularities in the vane may make important nonlinear terms in the capacity between the vane and the quadrants. Although the maximum charge sensitivity is not affected by this distance, the optimum voltage and the voltage sensitivity are affected.

The instrument is leveled until the piece holding the vane is in the center of the circular hole in the top of the box. A grounding switch, which may be manually or magnetically operated, must be provided. Care should be exercised not to introduce variable thermal e.m.f.'s.

The torsion head should be adjusted so that each half of the vane lies as nearly as possible symmetrically between two quadrants. With the vane grounded, small values of $+V$ and $-V$ are applied to the quadrants. Adjustment is made to the torsion head in the appropriate direction, so that whether a potential is on the quadrants or not, no motion of the vane takes place. After the full values of $\pm V$ are placed on the quadrants, slight adjustments can be made with the potentiometer as shown in Figs. 10(b) and 10(c). This procedure is generally known as bringing the mechanical and electrical zeros together, and must be done with all forms of electrometers.

In operation, the actual useful working value of the charge sensitivity will be about

$$
\begin{aligned}
S_q &= 1.3 \times 10^4 \text{ div./statcoulomb} \\
&= 0.4 \times 10^{14} \text{ div./coulomb} \\
&= 0.6 \times 10^{-5} \text{ div./electron.}
\end{aligned}
$$

The corresponding voltage sensitivity will probably lie in the range

$$S_V = 1000 \text{ to } 1500 \text{ div./volt,}$$

while the optimum value of the voltage applied to the quadrants will probably be between 50 and 100 volts on

each side of ground, or if the high potential is placed on the needle, it will usually be between 100 and 200 volts, depending, among other things, on the size of the torsion fiber.

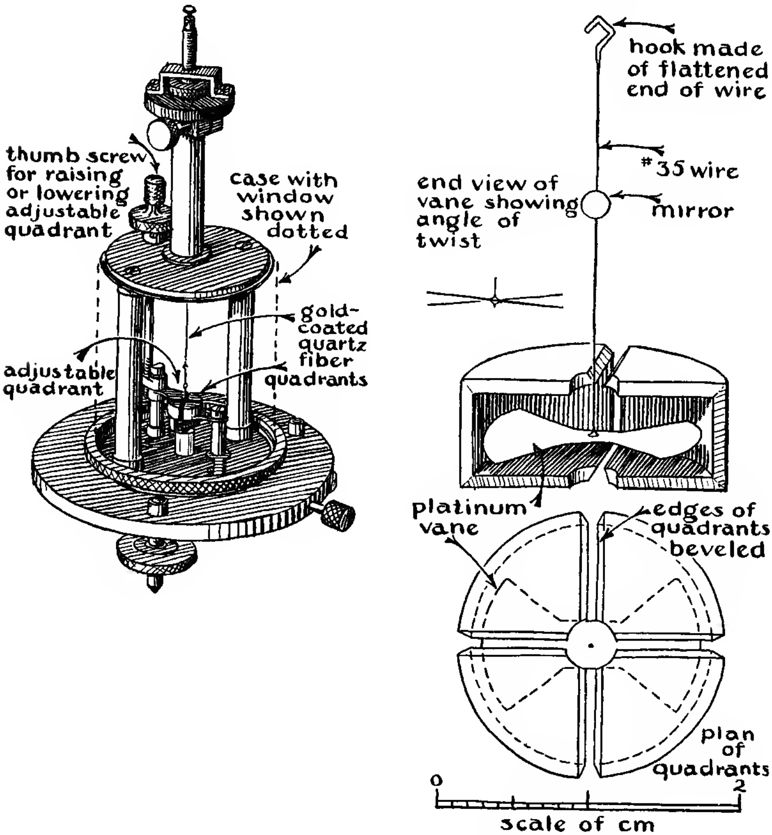


Fig. 11. Compton adjustable quadrant electrometer.

It is assumed in the above that a scale with 1-mm divisions is used at the customary distance of 1 m.

The Compton electrometer[8] was introduced in 1919 by the two Compton brothers.[9] It is of the quadrant type but is so

[8] This instrument is made by the Rubicon Company, 29 North Sixth Street, Philadelphia, and by the Cambridge Scientific Instrument Company, Ltd., Cambridge, England.

[9] Compton, A. H. and K. T., *Phys. Rev.*, *14*, 85 (1919).

arranged that one quadrant can be raised or lowered with respect to the other three. Further dissymmetry is introduced by giving the vane an initial tilt. By proper adjustment of this movable quadrant the time consumed by the needle in returning to its initial position after a deflection may be lengthened (negative control) or shortened (positive control). The design of the instrument is shown in Fig. 11. The dissymmetry introduces additional nonlinear terms

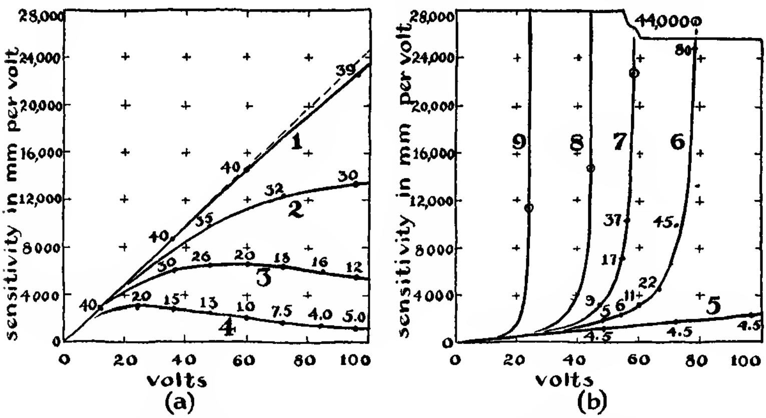


Fig. 12. Typical curves of the Compton electrometer showing the effect of various degrees of positive (a) and negative (b) control on the voltage sensitivity. The curves in (b) were taken with a much stiffer fiber than those in (a).

into the change of capacity as the needle moves, and an electrostatic torque is introduced which either opposes the torque of the suspension (negative control) or aids it (positive control). In the extreme case the action of the suspension can be more than completely neutralized, so that an unstable instrument results. This means that the voltage sensitivity can be made extremely high. Fig. 12(a) illustrates the relationship between the voltage sensitivity and the voltage on the needle for different degrees of positive control, while Fig. 12(b) shows the same relationship for various degrees of negative control. In this latter case a stiffer suspension was used. The circles on curves 6, 7, 8, 9 represent the highest

sensitivity at which the zero of the instrument is sufficiently stable to allow satisfactory measurements to be made. The small figures above the curves of Figs. 12(a) and 12(b) represent the time required in each case for the needle to return to within 1 mm of the rest position after a deflection of 50 mm. Because of the small restoring torque and high air damping, the motion of the suspended system is aperiodic.

Where extremely small potentials are to be measured and where the demand on charge sensitivity is not too great, the Compton electrometer is very suitable. However, the same voltage sensitivity could be achieved with the usual quadrant electrometer by putting in a suspension fine enough to give the same time of return to zero, provided that the moving system were equally as light as that in the Compton. In fact, it will be noted from the curves that with neither positive nor negative control, shown by the straight line of Fig. 12(a), but with a fine fiber, voltage sensitivities can be obtained equal to those with a stiff fiber and large negative control. This high voltage sensitivity is not always useful when measuring electric charges, which is the main purpose of electrometers, for not only does the instrument become very sluggish, but drifts become bad. Also, for a given time of return from a given deflection the charge sensitivity has a maximum value.[10] Wolf[11] states that the maximum usable charge sensitivity of the Compton electrometer is 2×10^{14} div./coulomb, which occurs at a voltage sensitivity of 5000 div./volt.

The Hoffmann electrometer[12] combines the highest charge sensitivity of any commercial instrument with stability, that is, lack of drift, and ease of working. Great care has been exercised to eliminate contact potentials, thermal e.m.f.'s, and air currents. To achieve the elimination of air currents, heavy copper pieces surround the movable

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[10] Pockman, L. T., *Rev. Sci. Instruments*, *7*, 242 (1936).

[11] Wolf, F., *Ann. d. Physik*, *18*, 373 (1933).

[12] Hoffmann, G., *Phys. Zeits.*, *13*, 480, 1029 (1912).

Hoffmann electrometers are made by E. Leybold's Nachfolger A. G. Köln-Bayental, Bonner Strasse 500, Germany.

system to insure that thermal gradients are kept at a minimum. A decided advantage is gained also by evacuating the case to a few millimeters of mercury, thus making the instrument "deadbeat."

The instrument operates upon essentially the same principle as the quadrant electrometer. The chief difference is

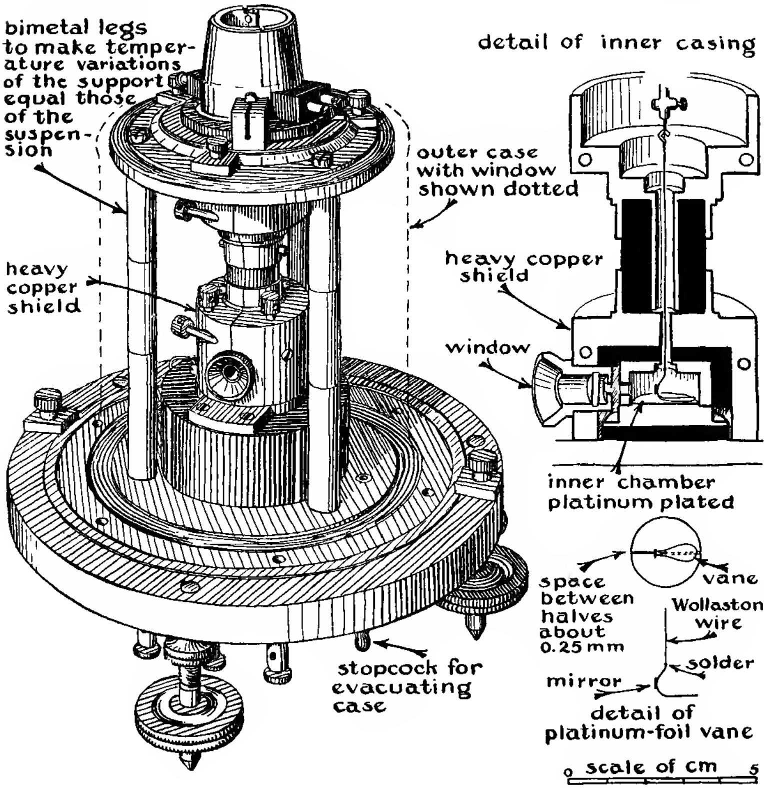

Fig. 13. The Hoffmann electrometer.

that a half vane is used for the movable system, so that, instead of quadrants, only two conductors, or binants, are necessary. Fig. 13 represents the relationships of the essential parts. The platinum needle and mirror together weigh approximately 5 mg, and the suspension is a 3μ (0.0003-cm) Wollaston wire.

To achieve a sensitivity independent of temperature, it is necessary to keep the vane or needle at the same distance from the binants. This is accomplished by inserting into the supports of the upper part of the electrometer case, which in turn supports the suspension, a metal of such coefficient of thermal expansion that the over-all expansion completely neutralizes the change of length of the torsion fiber with temperature.

Contact and thermal electromotive forces are kept at a minimum by making everything from or plating it with platinum. Also, insulation is protected by metal, so that possible spurious charges cannot affect the system.

Since the Hoffmann electrometer combines so many desirable features, it may be well to list some of them. These characteristics must be combined in any other instrument with which it is intended to push the charge sensitivity to that limit set by Brownian motion, and still have freedom from drift and a reasonable working period.

1. The moment of inertia of the moving system must be small. (See Eq. 13.)
2. The suspension must be made of material which has a small coefficient of internal friction; that is, the needle must return to zero after a deflection.
3. Air currents must be kept at a minimum. This means that the moving system must be surrounded with heavy copper pieces. The suspension should be closely surrounded by metal pieces as well.
4. The case must be evacuated to keep the working time within a reasonable limit.
5. Temperature compensation is needed if the distance between the vane and the stationary parts is to remain constant.
6. Thermal and contact electromotive forces must be eliminated.

In addition to the above, it is usually desirable to have the scale approximately linear.

Two additional features of the Hoffmann electrometer are (1) an electromagnetic grounding switch and (2) an induction ring for inducing a charge on the movable system.

To facilitate making the necessary electrical connections, a control mechanism is supplied with the instrument when it is purchased. Although not absolutely necessary, the control mechanism is a great aid, since the proper connections are made and broken at the right time by only one operation.

The latest model of the Hoffmann electrometer[13] combines all the desirable features of the earlier models but permits greater accessibility to the essential parts. Also the adjustments are much more easily made; for example, in the older types the instrument had to be exhausted after adjusting the binants, while in the new design this adjustment is made through a sylphon from the outside.

String electrometers are divided into two main divisions: (1) those with a fiber supported only at one end and (2) those in which the fiber is kept taut by a fine spring. The latter are the most common and, as far as is known, are the only ones on the market.

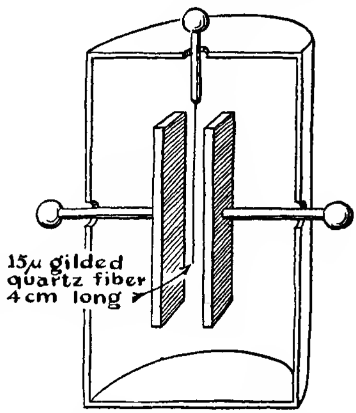

Fig. 14. An easily constructed quartz-fiber electrometer in which the fiber is supported only at one end.

Electrometers of the first class are easily made and are often very satisfactory when high sensitivity is not needed. The two plates can be flat and the fiber hung down between them as shown in Fig. 14. There should be an adjustment either on the plates or on the fiber or on both to bring the mechanical and electrical zeros together. Some adjustment may be made by tipping the instrument in the appropriate

[13] Zipprich, B., *Phys. Zeits.*, *37*, 35 (1936).

direction. A microscope must be provided to read the deflection. With the plates 1 cm apart, the fiber should be about 25μ in diameter and 4 cm long if the potential on the plates is not to exceed 100 volts.

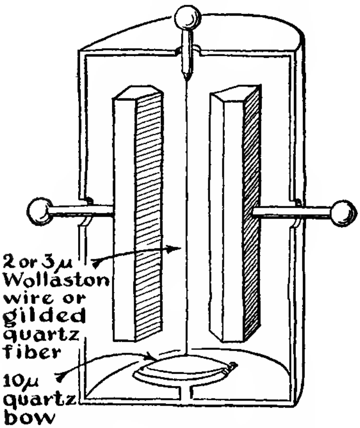

Fig. 15. Schematic diagram of the Wülf string electrometer.

Of the second type, that designed by Wülf[14] is, perhaps, typical. It is shown diagrammatically in Fig. 15. The fiber is usually a Wollaston wire 2μ in diameter, kept taut by a quartz-fiber bow. Screw adjustments permit movement of the plates with respect to the fiber as well as change in the tension of the fiber.

With all string electrometers the deflection is not a linear function of the applied charge or voltage at high sensitivity. It frequently happens that at high sensitivities the fiber leaves the field of view of the microscope as it reaches a position where instability occurs.

The chief advantages of string electrometers are (1) portability, (2) ease of adjustment, and (3) short working time.

The Perucca electrometer[15] is similar to the string electrometer, except that the part between the plates consists of

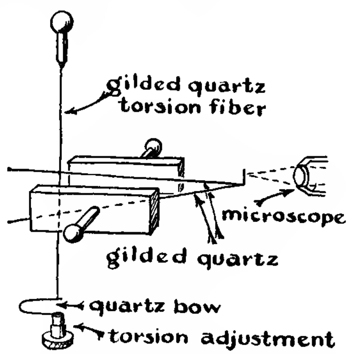

Fig. 16. Principle of operation of the Perucca electrometer.

[14] Wülf, Th., *Phys. Zeits.*, *15*, 250, 611 (1914).
This instrument is made by E. Leybold's Nachfolger A. G. Köln-Bayental, Bonner Strasse 500, Germany.
[15] Perucca, E., *Zeits. f. Instrumentenk.*, *47*, 524 (1927).
This instrument is obtainable from E. Leybold's Nachfolger A. G. Köln-Bayental, Bonner Strasse 500, Germany.

two conducting quartz fibers supported on a torsion fiber as shown in Fig. 16. The two movable fibers are brought together at one end, and a small index, which is viewed with a microscope, is provided. The charge and voltage sensitivities are each greater than can be obtained with a string electrometer. Not only is it more sensitive, but it also combines all the advantages of the latter instrument.

The Lindemann electrometer[16] was developed primarily for use with photoelectric cells mounted on telescopes in measuring light from stars. Such use requires that the sensitivity and position of the moving system be independent of

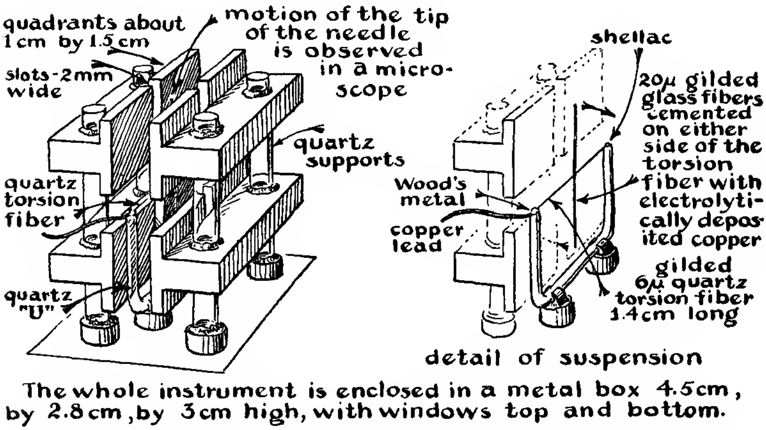

Fig. 17. Arrangement of quadrants and movable system in the Lindemann electrometer.

tilt. The first is accomplished by making all parts very rigid and the second by using for the moving system a light needle mounted on a stretched torsion fiber. Since a mirror and scale would be cumbersome for such uses, the deflection of the needle is read with a microscope with a micrometer ocular. The whole electrometer weighs but 80 g. The quadrants and needle mountings are represented in Fig. 17.

[16] Lindemann, F. A. and A. F., and Kerley, T. C., *Phil. Mag.*, *47*, 577 (1924).

This instrument is obtainable from the Cambridge Scientific Instrument Company, Ltd., Cambridge, England.

The principle on which the instrument works is similar to the quadrant electrometer. The quadrants are 1.5 cm broad and 1 cm high, with a slot 2 mm wide, into which the needle may pass, cut in each. These plates are mounted 5 mm apart on quartz rods. The torsion-fiber mounting and needle are placed between the plates so that the junction of the needle and torsion fiber is symmetrically located with respect to the four plates. The whole is mounted in an aluminum box with suitable connections. Through a glass window in one side of the box the motion of the end of the needle is observed with a microscope. A window directly opposite on the other side of the case permits light to enter.

The needle may be balanced so that a rotation of the instrument through 90° makes less than 0.06 mm motion of the end. The needle is usually about 1 cm long, and the torsion fiber is 6μ in diameter. The needle and torsion fiber are covered with a conducting coating of metal, and a suitable connection is made to the outside of the case. The quartz frame for holding the torsion fiber serves as insulation as well.

Electrical connections are the same as for any quadrant electrometer. Instability occurs at a potential of about 100 volts. At 3 volts below this unstable value the deflection will reach 99 per cent of its final value in 1 second. The voltage sensitivity under these conditions is 0.76 mm/volt motion of the end of the needle. With a suitable microscope a workable sensitivity of 500 div./volt can be obtained. The electrostatic capacity is about 2 cm.

The instrument may conveniently be used with a leak to measure currents of from 10^{-10} to 10^{-14} ampere. When not too great demands are to be met, this quite inexpensive electrometer will meet many needs, especially where portability is a requirement.

For a discussion of circuits, sensitivities, and limitations of the vacuum-tube electrometer, which uses specially constructed vacuum tubes, see Chapter X.

Some practical considerations in the use of electrometers and electroscopes. *Useful sensitivity in X-ray work.* Electrometers are frequently used with an ion chamber in X-ray work. As is well known, ions are formed not only by the X-ray beam but by (1) cosmic rays, (2) local radiation from radioactive matter in the surroundings, and (3) radioactive contamination on the inner walls of the ion chamber. Of these, (3) can be reduced to a small value in comparison with the others by two effective means. The inner walls can be painted with a mixture of collodion and lampblack, each of which is quite free from radioactive materials. The thickness should be about 0.05 mm to stop all the α particles. The other method is to maintain a fine wire grid at a suitable potential to drive the ions formed by the α particles back into the walls. Since in general (3) is due to particles which will have a range of less than 5 cm at normal air pressure, the range can be kept within the grid by a gas of high molecular weight or increased pressure, or both. Even rubbing Carborundum paper on the walls of the chamber will often help considerably in lowering the emission. As for (1), cosmic rays could be reduced to an extremely low value by going into a mine 100 to 200 feet below the surface of the ground, while (2) could be made negligible with 4 inches of surrounding lead. However, since it is not practical to go to such trouble, in most cases it is necessary to make the best of the situation.

Since the error of a result which depends on the difference or sum of two readings is[17]

$$\epsilon = (\epsilon_1^2 + \epsilon_2^2)^{1/2}, \tag{16}$$

where ϵ_1 and ϵ_2 are the errors of the two readings, it is hopeless to try to push the sensitivity of the measuring device beyond a certain point, and the only hope of increasing accuracy is by a longer period of observation. It is easily seen that the optimum useful value of the sensitivity is

[17] For a further discussion of probabilities and errors involved when a measurement depends on the effects of a finite number of particles, see page 298.

reached when the deflection due to background only and the deflection due to the X-ray beam only are equal for the same time of observation.

If the ratio of background to beam readings is to be made as small as possible, it is obvious that the volume also should be made as small as possible, since the background reading goes up with the volume.

Example. Assume an ion chamber of 1000 cm^3. Cosmic rays will contribute about 3 ions/cm^3/sec./atmosphere of air at sea level. Local radiation will be from 3 to 5 I (ions cm^{-3} sec.$^{-1}$ atmosphere^{-1} of air), while the background may vary over wide limits; from 0.1 to 10 ions cm^{-3} sec.$^{-1}$ atmosphere^{-1} of air will probably include the extreme cases. Since the α-particle paths will usually end in the gas, an increase of pressure will not change the number of ions formed by the α particles, but the ionization due to local radiation and cosmic rays will go up as the pressure increases. Let us assume $7I$ as due to electrons and $5I$ as due to α particles. The average path length of the electrons is about 10 cm, and at 60 ions/cm of path this corresponds to about 12 electrons/sec. crossing the chamber. In order to have a mean relative error of ϵ_1, then according to the laws of probability, $1/\epsilon_1^2$ particles must cross the chamber. Let ϵ_1 be 0.03, or 3 per cent; then 10^3 particles must be counted. This will take 80 seconds on the above assumptions. These 10^3 electrons will form 6×10^5 ions. Hence if we assume the same fluctuations in the ions from the beam, then according to Eq. 16, to have an average error of 4 per cent in a reading, we must time for at least a minute, and the sensitivity of the electrometer need not be greater than 10^{-5} div./ion if we estimate to 0.1 div.

As for the α particles from the walls, their effect may be considered as follows: Supposing they amount to $5I$, which is not an uncommon value, then there will be 5000 ions/sec. formed. Now an α particle will form, on the average, about 10,000 ions in the gas. Hence there is 0.5 α particle/sec. emitted by the walls. Now if ϵ_1 is the mean absolute error

in a given reading and ϵ_2 in another reading, the mean relative error ϵ_r in the sum will be

$$\epsilon_r = \frac{(\epsilon_1{}^2 + \epsilon_2{}^2)^{1/2}}{\theta_1 + \theta_2}, \tag{17}$$

where θ is the deflection of the instrument. If N_1 is the number of particles per second of one kind of particle and I_1 the number of ions formed per particle, then it can be shown from Eq. 17 that the mean relative error of the sum is

$$\epsilon_r = \left(\frac{N_1 I_1{}^2 + N_2 I_2{}^2}{t(N_1 I_1 + N_2 I_2)^2}\right)^{1/2} = \left(\frac{(4.3 + 50) \times 10^6}{t(0.72 + 0.50)^2 \times 10^8}\right)^{1/2} = \frac{0.6}{t^{1/2}}$$

under the above assumptions if the subscript 1 refers to the electrons and 2 refers to the α particles. It is then necessary to count for 400 seconds to gain an accuracy of 4 per cent. In this time 5×10^6 ions will have been collected. In order to read this to 4 per cent we need a sensitivity no greater than 10^{-6} div./ion.

The above calculations have been made to show (1) the importance of eliminating α particles as much as possible and (2) that when this is done completely, the sensitivity of the electrometer has a limit beyond which there is no gain.

If charges are to be collected where there is very little background, such as in photoelectric work, then there is no reason why the sensitivity cannot be pushed to the maximum. In all cases, if possible, an electrometer or an electroscope suitable to the accuracy required should be chosen.

Useful sensitivity in cosmic-ray work. In case the instrument is subject only to cosmic rays and no shielding is used, the ionization is due to random electrons and "X" particles, which ionize the gas the same as electrons. When this is so, the mean relative error is $N^{-1/2}$, where N is the total number of particles, the effects of which are measured. If there are n high-energy particles/cm²/sec., and if the mean relative

error is ϵ_r for one reading, then we must observe for a time

$$t = \frac{1}{\epsilon_r^2 \pi n R^2},$$

where

$$\frac{1}{\epsilon_r^2} = N,$$

for a spherical ionization chamber, and if σ is the specific ionization, since the average path length is $\frac{4}{3}R$, the total number of ions collected in the time will be

$$\nu = \frac{4}{3}\frac{\sigma R}{\epsilon_r^2},$$

and this must give a deflection which can be read with no larger relative error than ϵ_r. If $\sigma = 60$ ions cm^{-1}, $R = 10$ cm, and $\epsilon_r = 0.01$, then $\nu = 8 \times 10^6$ ions, and we need a sensitivity of about 3×10^{-6} div./ion. Now $n \cong 0.02$ electron/cm^2/sec. at sea level. Hence the minimum time of observation should be 30 minutes, and for each observation the mean error will be 1 per cent. This calculation, of course, neglects the error introduced by the background radiation.

Frequently, however, the ionization chamber is surrounded with shields made of iron or lead. These do two things: (1) In general, they lessen the intensity of the radiation, and (2) they introduce new radiations. All the particles passing through the ionization chamber are no longer randomly distributed in time, for, in addition, there now exist showers, consisting of from two to several hundred electrons, which come all at the same time from some region of the shield. These introduce larger fluctuations than would otherwise exist, and the time of observation for the size of ion chamber assumed above may be from two to four times as long for the same error, and a correspondingly less sensitivity of the measuring instrument will serve the purpose.

Steady deflection measurements. In some cases it may be desired to use the constant deflection instead of the drift method. This may be done by using the electrometer to

measure the drop in potential across a fixed resistance as shown in Fig. 18. Assume that it is desired to measure a constant ion source I. Let the capacity to ground of the external system be c_1 and of the electrometer c_2, and let the drop in potential be measured across R_1. Then

$$i_1 + i_2 = I',\ i_1 = \frac{V}{R_1},\ i_2 = \frac{dQ_2}{dt} = c_2\frac{dV}{dt},$$

$$I = \frac{dQ_1}{dt} + I' = C_1\frac{dV_1}{dt} + I',\ V = i_1R_1.$$

The equation for the potential across the electrometer is then

$$V = \left[I - (c_1 + c_2)\frac{dV}{dt}\right]R_1.$$

Solving and putting in the boundary condition that when $t = 0,\ V = 0$,

$$V = IR_1\left[1 - e^{-\frac{t}{(c_1+c_2)R_1}}\right].$$

Thus the potential across the electrometer rises exponentially. If we say arbitrarily that we shall wait until the deflection is 99 per cent of the ultimate deflection, then we must wait a time $t = 4.6\ R_1c$, where $c = c_1 + c_2$. The deflection will be approximately VS_V after this time. Had we measured I by the drift method, we should have the same deflection in a time R_1c, the difference, of course, being due to the fact that in the second case the drift is constant, while in the first case the drift begins at the same rate, that is, as if $R_1 = \infty$, but gradually slows down, becoming very slow toward the last.

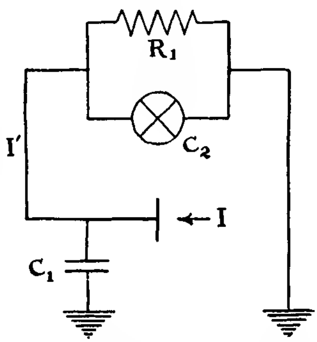

FIG. 18. Measuring an ion current I by determining the potential drop across a resistance R_1 by means of an electrometer, c_2.

It is therefore much more satisfactory to use the drift method for measuring feeble currents, while larger currents

are conveniently measured by the steady deflection method. The drift method can be used in measuring large currents also by inserting a capacity of the appropriate value to lengthen the time of drift.

Limitations of various types of instruments. Limitation on the charge sensitivity of electroscopes and electrometers has already been pointed out. For the former the maximum charge sensitivity is

$$(S_Q)_{\text{max.}} = \frac{1}{2}(ck)^{-1/2} = \frac{1}{2V_0b},$$

and for the latter

$$(S_Q)_{\text{max.}} = \frac{1}{2}(2ck)^{-1/2} = \frac{1}{4V_0b}.$$

The capacity of an electroscope which has no external lead will depend on the particular design, but for the Wülf or torsion type it will lie between 0.4 and 1 cm. That of an electrometer with its added external capacity will probably be between 20 and 100 cm. The restoring constant, k, of the suspension can be reduced in each to a point where the sluggishness of the motion makes the instrument tedious to work with, or in the case of most electroscopes, where the collecting potential becomes too small to collect most of the ions. Since an electrometer case can be evacuated, it is possible to adjust the pressure until the motion of the vane or needle becomes critically damped.

If the electrometer case is not evacuated, the working period may become excessively long when high sensitivities are desired. Much can be achieved by making the needle or vane small and light, as is done in the Lindemann and Perucca electrometers, and as is inherently the case with string electrometers.

Limitations imposed by drift. The amount of drift during a reading is often the limiting factor in electrometers. This frequently becomes bothersome long before the maximum sensitivity has been reached. One of the chief reasons for the drift is that the mechanical and electrical zeros gradually

drift apart. The deflection caused by the zeros being different may be many times the actual amount they are apart. Drift, among other causes, is due to (1) fluctuations in battery voltage and (2) nonelastic changes of strain in the suspension. If the drift were constant, proper allowances could be made, but there are so many factors which depend in a different way upon changes of voltages, temperature, humidity, and so forth, that it is often very difficult, if not impossible, to eliminate completely or take account of the drift. This is especially true with vacuum-tube electrometers, even though balanced circuits are used.

Limitations on the amount of useful magnification. Two methods are in general use for determining the amount of deflection in an electroscope or electrometer: (1) Microscope with micrometer ocular and (2) mirror and scale. For the Lindemann electrometer and most electroscopes the microscope is used. The limitation as far as magnification is concerned amounts to a limitation of resolution. Magnification can continue until the position of a diffraction band cannot be located to within 0.1 div. in the eyepiece. Beyond this, nothing is gained. With a numerical aperture of 1 and an image distance of 20 cm the shortest useful focal length is about 3 mm with a 100-div. scale in the eyepiece 1 cm long.

If a mirror and scale are used, there is a certain minimum mirror size which will allow sufficient resolution. With a 1 mm div. scale at the customary distance of 1 m, it is necessary to have a mirror at least 2 mm in diameter to read to 0.1 div. on the scale.

In all cases, whether in resolution, amount of drift, fluctuations, or the like, it *should always be possible to estimate to 0.1 of the smallest division* on the scale, and in general it is *useless to push the sensitivity of any instrument beyond the point where 0.1 div. loses its significance.*

Limitations imposed by Brownian motion. It is part of the classical theory of the equipartition of energy that all bodies have a mean thermal energy of $\frac{1}{2}KT$ for each degree of freedom, where K is Boltzmann's constant and T the

absolute temperature. This Brownian motion of the instrument is evidenced by random fluctuations about the point of equilibrium. It is evident that before a superimposed steady deflection can be detected, it must be at least as large as this mean Brownian deflection.

The mechanical energy of a moving system with a restoring force proportional to the displacement is $\frac{1}{2}k\xi^2$, where k is the restoring force (or torque) per unit of displacement. If $\Delta\xi$ is the mean Brownian deflection, then the k corresponding to this is given by

$$\tfrac{1}{2}k(\Delta\xi)^2 = \tfrac{1}{2}KT,$$

or

$$k = \frac{KT}{(\Delta\xi)^2}.$$

Now with the electroscope the maximum charge sensitivity is reached when $S_Q = \frac{1}{2}(ck)^{-1/2}$. Consequently, the corresponding charge sensitivity is

$$S_Q = \frac{\Delta\xi}{2(KTc)^{1/2}},$$

if the deflection is equal to the mean Brownian deflection. At room temperature the maximum charge sensitivity is thus limited for electroscopes to

$$(S_Q)_{\text{max.}} = \frac{1.2 \times 10^{-4}}{c^{1/2}} \text{ div./electron},$$

where c is in centimeters. For electrometers the expression becomes

$$(S_q)_{\text{max.}} = \frac{0.8 \times 10^{-4}}{c^{1/2}} \text{ div./electron}.$$

It is obvious that the electrostatic capacity of the instrument should be as small as possible if it is intended to push the charge sensitivity to the limit. Inherently the capacity of the electroscope is much less than that of the electrometer. This not only makes it possible to have a higher charge sensitivity for the same torsion constant but allows it to be used.

It is interesting to compare the above limit with that obtainable with a Geiger counter. In some applications the number of counts and the number of unit charges collected are comparable. The mean error with a Geiger counter in a single count of N particles distributed at random is $N^{1/2}$, so that if it is desired to have a mean relative error of 1 per cent, it is necessary to count $1/(0.01)^2$ or 10^4 particles. With an electroscope having a capacity of 0.5 cm, it is necessary to collect 8×10^4 electrons to have the same mean error if the deflection can be read to 0.1 div. This is, of course, disregarding the backgrounds in each case.

A comparison of various types of instruments. Probably the most sensitive electrometer on the market is the Hoffmann. The maximum sensitivity which can be reached with this instrument is approximately 5×10^{15} div./coulomb. Drift has been eliminated to such an extent that sufficient time can elapse to detect an average of 1 electron/sec. For ease of working, however, it is advisable to keep the charge sensitivity in the neighborhood of 1×10^{15} div./coulomb. Much is gained in the Hoffmann by evacuating the case, thereby not only shortening the working time but greatly eliminating the effects of convection currents.

The vacuum-tube electrometer has gained much favor in the past few years. It has the advantage that it can be used in places where it would be inconvenient or impossible to use the conventional type of electrometer. The sensitivity can be made comparable to that of the Hoffmann, although it is very much inferior as far as drifts are concerned. Ordinary precautions consist in having large storage batteries for plate and filament supply which are kept at as constant a temperature as possible, with all leads well shielded. Resistances must also be kept constant. Although with the proper circuit and circuit constants the effects of voltage fluctuations are reduced to a minimum, it is still not possible to eliminate the drift, and it is usually necessary to wait several hours after the connections are made for conditions to become only approximately steady.

When possible, an instrument should be chosen for the problem at hand. Frequently it is desirable to use an electroscope in place of the electrometer. The advantages to be gained may be listed as follows: (1) Freedom from external changes of temperature and humidity, (2) freedom from changes in battery potentials and resistances, (3) freedom from drifts, (4) need for only one potential, (5) ease of setting up and operating, (6) portability, and (7) low cost. The disadvantages are that (1) except with the torsion type the sensitivity is not as high as with the ordinary electrometer, (2) the sensitivity is not readily varied, and (3) it is not convenient to use a null method of reading.

In Table I are listed the approximate characteristics of some instruments. The values of charge sensitivities listed are not the maximum attainable but represent those that

TABLE I

COMPARISON OF CHARACTERISTICS OF VARIOUS INSTRUMENTS

Type	S_V	S_q ($\times 10^{14}$)	Working Period (seconds)
Wülf bifilar	0.5	0.002	0.1
Wilson tilted	100	0.1	....
Neher torsion	100	2	1
Dolezalek quadrant	1000	0.4	60
Compton	5000	2	40
Lindemann	500	0.5	1
Wülf string	500	0.2	1
Perucca	2000	1	10
Hoffmann vacuum	10,000	10	10
Vacuum tube	10,000	5	....

Units of voltage sensitivity, S_V, are divisions per volt which correspond to the maximum usable charge sensitiyity, S_q, expressed in divisions per coulomb. Values of S_q are for no added external capacity.

can be reached and worked without great difficulty. The values of the voltage sensitivities are those which correspond to these values of the charge sensitivities. In some cases the voltage sensitivity can be made much higher, in particu-

lar with the Compton, with which it is possible to reach 50,000 div./volt. The working period represents approximately the time for the deflection to become zero after the net charge is removed.

Useful techniques in electroscope and electrometer work. *Mounting gold leaves.* Gold leaf usually comes in sheets about 8 cm square, the leaves being separated by sheets of tissue paper. The leaf will be found quite uniform and thin enough so that objects can be distinguished through it when it is held before the eye. The thickness is usually about 0.08μ. The leaf is cut to the desired size by placing it between sheets of tissue paper and using a razor blade. The paper separating the gold leaf will be found satisfactory for the purpose. The cutting should be done on a flat base, such as cardboard. If the razor blade is sharp, the cut will be clean and the gold will not adhere to the paper. The leaf can be moved around from one sheet of paper to another by means of clean needles, mounted so that they can be handled with ease. It can also be picked up with clean fine-pointed tweezers. If the leaf touches anything which has a film of organic substance on the surface, it will easily adhere with only slight pressure. Once the leaf has stuck, it will usually tear before coming loose. It is safest to handle it as little as possible. When mounting the foil on the single-leaf type of electroscope, it is cut to size and then transferred to a piece of paper, such as typing paper, and placed so that one end of the leaf is near one edge of the paper. The edge of the paper is allowed to overhang the table about $\frac{1}{4}$ inch. Some alcohol-dissolved shellac is spread across that part of the metal piece from which the leaf is to hang. The edge of this shellac must be perpendicular to the edge of

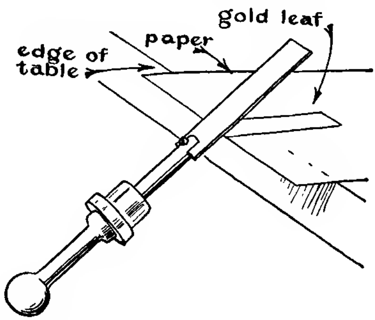

Fig. 19. **Mounting the leaf on a gold-leaf electroscope.**

the metal support, in order that the leaf, when mounted, will deflect in a plane perpendicular to the plane of this support. The metal piece must be clean, or the leaf is apt to adhere to it. The metal support is brought into position as shown in Fig. 19 and then lowered gradually. The paper will bend and the leaf will adhere to the shellac.

The above operations should be carried out in a room in which the motion of the air is at a minimum. It is often advisable to wear a mask or deflector over the nose to avoid blowing the leaf about.

Preparation of Wollaston wire.[18] The Hoffmann and many string electrometers use a fine platinum suspension known as Wollaston wire. It may be obtained in various sizes from 1.5μ to 5μ. To produce such a fine wire of uniform size, the following process of manufacture is used. Upon a much larger platinum wire is electroplated a uniform layer of silver. The combination is then drawn down until the fine thread of platinum in the middle is of the proper size. The silver is etched off with acid. Since the resulting platinum wire is quite delicate, special care must be used in the etching as well as in subsequent handling.

In order to avoid small bubbles collecting on the wire and interfering with the etching, or in some cases breaking the fine wire, a special solution of chemically pure nitric acid in distilled water at a density of 1.10 g cm^{-3} is used. To insure uniform etching, the wire should be thoroughly cleaned before it is immersed in the acid. As an aid to handling after etching, a bead two to three times the diameter of the silver wire is formed on one end with a small oxygen flame before the silver is etched off. A section of wire is then cut off, perhaps an inch longer than the necessary suspension. The solution is placed in a tall vessel, such as a graduate, and the straightened silver wire is supported in it vertically. The suspension should be left in for a longer rather than a shorter time, since the platinum is not damaged by the solution.

[18] Wollaston wire is obtainable from Hartmann and Braun, A. G., Frankfurt am Main, Germany, and Baker and Company, Philadelphia.

It is necessary that all the silver be etched off, or the suspension may be ruined in the annealing process. The small bead marks the lower end as the suspension is drawn from the solution. Before soldering it into place, it may be desirable to mount the suspension on a "wishbone," the distance between the two prongs being somewhat greater than the length of the mounted suspension. If quartz fibers 20μ to 30μ in diameter are mounted in the tips of the prongs and the Wollaston wire is fastened to these with a hard wax, there will be much less chance of breakage.

Either before or after mounting, the suspension should be placed in a horizontal position and annealed with a small gas flame. In still air the flame is passed beneath at such a distance that the platinum is heated to a bright red color. If all the silver has been etched off, the suspension will appear a uniform brightness throughout its length. The annealing is necessary, if the wire is to be used in an electrometer, to relieve the strains which resulted from the drawing.

In soldering the suspension in place, a c.p. solution of zinc chloride is a good flux. The heat is best applied with a small soldering iron, not directly at the point at which the suspension touches the solder but at a short distance away, relying upon the conductivity of the metal support. It is best to work under a magnifying glass or, better still, a binocular microscope. The joint should be rigidly inspected to see that the platinum is actually embedded in the solder and not just held by the solidified flux.

Insulators used in electrometer and electroscope work. The insulator ordinarily used in electrometers is amber. The amber now on the market is usually a manufactured product which has as good insulation properties as the natural amber and has the advantage of being obtainable in a variety of sizes. Amber has a high volume resistivity, and the surface resistance of clean amber is also high. If the surface is contaminated, the best remedy is to remove some of the amber with a clean tool by turning it in a lathe. If

this is not convenient, the amber may be covered with a thin coat of ceresin, as will be described later.

The best insulator known is clean, dry, fused quartz. By clean quartz is meant quartz which has not touched anything since being heated to the softening point, and by dry quartz is meant quartz either in a good vacuum or in a gas dried by phosphorus pentoxide. Fused quartz is also superior to other insulators in that the soak-in is far less. Under comparable conditions amber has at least ten times the soak-in possessed by quartz.

Ceresin is a natural wax which has remarkable electrical insulation properties.[19] It is about the same hardness as ordinary paraffin, each at 20°C. However, it has a somewhat higher melting point than either paraffin or the artificial ceresin, being liquid at 65°C. Its insulation properties have been measured by Curtiss[20] of the Bureau of Standards. He gives the surface resistivity as greater than 10^{17} ohm cm even at 90 per cent humidity. One of its main uses in the laboratory is to improve the surface resistance of other insulators. If the solid insulator and the ceresin are each heated to around 100°C. and a light coating of ceresin applied, the surface leakage will usually be found greatly reduced, sometimes by a factor of 100.

[19] Natural ceresin is distilled from the mineral ozokorite. An artificial ceresin, which is inferior to the natural product, is also on the market. In ordering, the natural product should be specified.

[20] Curtiss, L. F., *Bulletin of the Bureau of Standards*, 1915.

CHAPTER VII

Geiger Counters

BY

H. V. NEHER

THE Geiger counter is an ion-magnifying device which is sensitive to individual ionizing particles. The resultant flow of charge, except for the so-called proportional counter, is practically independent of the number of ions formed by the original particle. Thus, in most Geiger counters an α particle forms from 10^2 to 10^3 times as many initial ions as a β particle; yet each gives rise to a pulse of nearly the same size, and each is usually registered as one particle.

These counters have now reached a practical state of high development as a means of studying feeble radiations, such as those found in cosmic rays and artificial or natural radioactivity. The mechanism of the gaseous discharge in the counters is, however, not well known.

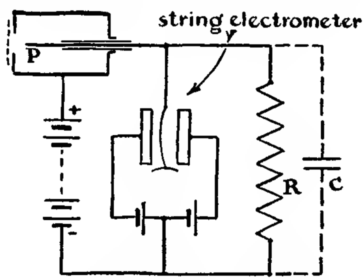

Fig. 1. The original point counter and circuit used by Geiger.

The point counter. The original design of Geiger[1] consisted of a pointed wire surrounded by, and insulated from, a metal cylinder as shown diagrammatically in Fig. 1. A high potential of 1500 to 5000 volts is applied across the counter, through a high resistance R (about 10^9 ohms). The cylinder is made

[1] Geiger, H., *Verh. d. D. Phys. Ges.*, *15*, 534 (1913); *Phys. Zeits.*, *14*, 1129 (1913).

positive with respect to the point P. The pulse is observed by means of a string electrometer.

Briefly, the action of the counter may be described as follows: The electric field immediately around the point is high enough so that at the pressure of the gas used any ion entering the space builds up by collision a large number of ions, which in turn build up more ions, until the quantity of charge which finally flows reaches the order of 10^{-8} coulomb, depending, of course, among other quantities, upon the applied potential. This charge, collecting on the distributed capacity, which may be represented by C, causes the potential across the counter to drop to a point at which the discharge can no longer be maintained, and the charge leaks off across the resistance R. The circuit then returns to its normally sensitive condition and is ready for a second count. The charge which builds up on C causes a drop in potential across R which is read by the electrometer.

The proportional counter. The counter just discussed operates on a trigger principle, and the size of the pulse is practically independent of the ionization of the initial particle, responding alike to α or β particles. However, Geiger and Klemperer[2] have found that if a small metal sphere is fastened to the point and made positive with respect to the cylinder, instead of negative as in Geiger's original design, over a limited range of voltage, that is, within the range A

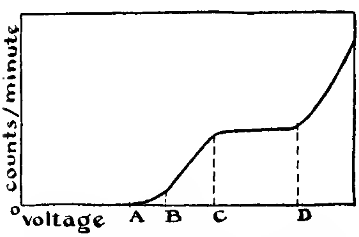

Fig. 2. Characteristic curve for the proportional Geiger counter. In the region from A to B the size of the pulse is proportional to the original ionization. In the region C to D the size of the pulse is practically independent of the amount of initial ionization.

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[2] Geiger, H., and Klemperer, O., *Zeits. f. Physik*, *49*, 753 (1928). See also the following:
Franz, H., *Zeits. f. Physik*, *63*, 370 (1930).
Klarmann, H., *Zeits. f. Physik*, *87*, 411 (1934).
Duncanson, W. E., and Miller, H., *Roy. Soc., Proc., A*, *146*, 396 (1934).
Haxel, O., *Phys. Zeits.*, *36*, 804 (1935).

to B in Fig. 2, the pulse is approximately proportional to the original ionization of the particle. This circumstance makes it possible to distinguish between heavy particles, such as α rays, protons, and deuterons, and the much lighter particles, electrons. Since γ rays show themselves by the electrons liberated from the material they pass through, it is also possible to count individual heavy particles in the presence of strong X-ray and γ radiation.

A design of proportional counter which has been used by a number of workers is shown in Fig. 3. The cylinder is

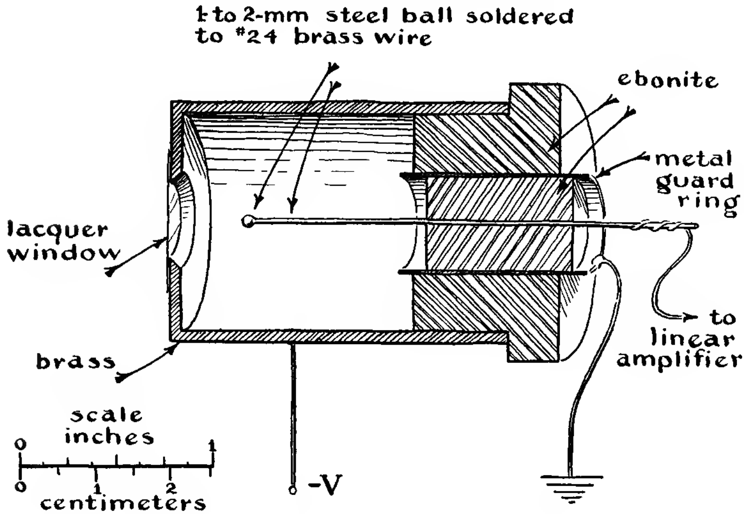

Fig. 3. Typical construction of a proportional counter.

maintained at a constant negative voltage with respect to the ball and wire. A steel ball from 1 to 2 mm in diameter will give good results, but the metal of which it is made is unimportant. The wire or rod supporting the ball may be made of almost any convenient metal, and is usually about one half the diameter of the ball. When a heavily ionizing particle enters the sensitive region surrounding the ball, negative charges are collected. The effect is amplified by a linear amplifier. Since the amount of charge collected is

proportional to the initial ionization, a means is here provided of distinguishing between heavy particles and electrons. A thin cellophane, lacquer, or mica window over the opening permits suitable gases to be used at reduced pressures. The threshold potential will probably lie between 1500 and 5000 volts, depending on the kind of gas used, its pressure, and the geometry of the counter.

Brubaker and Pollard[3] have studied the effects of various gases, using different kinds of heavy particles. Their recommendations are to use argon at pressures greater than 50 cm of mercury if there is a background of γ radiation, while for α-particle or proton-scattering experiments, where γ rays are not serious, hydrogen, nitrogen, or air between 2 and 10 cm of mercury pressure can be used.

If the potential on the above counter, with the small sphere in place of the point, is raised, a region C to D in Fig. 2 is reached where the effect of all particles is practically the same and the number of counts per unit time becomes almost independent of the applied voltage for a constant radiation. The length of this "plateau" depends primarily upon the distributed capacity and the resistance across the counter. When the point D is reached, the number of counts for a given radiation begins to increase, and any further increase in voltage soon sets up a steady gaseous discharge.

Since the sensitive portion in a point counter is limited to a small region in the immediate neighborhood of the point, it is useful primarily in experiments in which only a small solid angle is to be studied at a time, such as in problems on scattering.

The "Zählrohr" or Geiger-Müller counter. When it becomes necessary to have a large area sensitive to ionizing particles, the point counter no longer can be used, and its place is taken by the Zählrohr or Geiger-Müller[4] counter (hereafter designated as the G-M counter). It has become particularly useful in the study of cosmic rays, for it is possi-

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[3] Brubaker, G., and Pollard, E., *Rev. Sci. Instruments*, *8*, 254 (1937).

[4] Geiger, H., and Müller, W., *Phys. Zeits.*, *29*, 839 (1928).

ble to use tubes of large cross-sectional area and thus have an accuracy comparable to that obtained with ionization chambers for the same time of observation. The advantages to be gained over the ionization-chamber method are that, by properly combining two or more G-M counters, (1) particles incident only from limited angles can be counted, and (2) background radiation due to contamination on the counter walls and radioactivity of the surroundings may be eliminated.

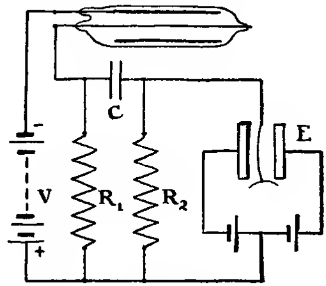

Fig. 4. A method for studying qualitatively the action of a Geiger-Müller counter, using a string electrometer as the detector.

Behavior of the G-M counter. Some of the properties of the counter may be studied by the arrangement shown in Fig. 4. The string electrometer, E, will be suitable, provided the counter is small, that is, the number of counts per minute is not more than 10 to 20. The circuit constants should be approximately as follows: $R_1 = 10^9$ ohms, $C = 30$ cm, and $R_2 = 20 \times 10^6$ ohms. The tube is made negative with respect to the wire.

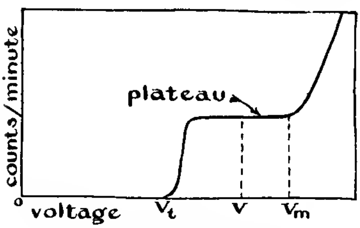

Fig. 5. Characteristic curve of a Geiger-Müller counter.

As illustrated in Fig. 5, when the potential, V, is raised, no effect will be noticed on the electrometer until a certain potential, known as the "threshold" voltage, V_t, is reached, when a small increase in potential will cause the number of counts per unit time to rise quite abruptly to a certain value.[5] Any further increase in the potential will cause

[5] The abruptness of this rise depends, to a large extent, on the ratio of the length to the diameter of the metal tube and on the position of the central wire. Owing to the end effects, the part of the tube which first becomes sensitive is that near the center. As the potential is raised, this active region moves out toward the ends, and soon practically the whole length becomes sensitive.

very little change in the counting until a potential V_m, which may be called the maximum operating potential of the counter, is reached. A small increase from here on will cause a sudden increase in counts, which soon goes over into a glow discharge. The "plateau" for a good counter and proper circuit constants may be 200 to 300 volts or even longer. This fact permits quantitative results to be obtained with G-M counters without elaborate means of regulating the voltage supply. The tube is usually operated at some intermediate voltage, V.

Although both positive and negative particles are present in the tube, the actual multiplying agents are probably the electrons. The electric field is higher than necessary for the electrons to form ions by collision, while it is probably not high enough for the positive or negative ions to do so. The electrons rushing toward the wire form new positive ions and electrons, the current building up according to the law $i = i_0e^{\alpha x}$, where α is the number of new pairs of ions formed per centimeter of path and is called the Townsend coefficient. Probably negative ions are also formed by the attachment of electrons to the molecules. In the ionization process light is given off, liberating new electrons from the metal tube, and these, in turn, form other ions as they rush toward the wire. This photoelectric process has been found by Christoph and Hanle[6] and by Locher[7] to be important in the mechanism of the discharge. The process of accumulative ionization continues until the potential difference between the cylinder and the wire has dropped to a point where ionization by collision can no longer occur. The po-

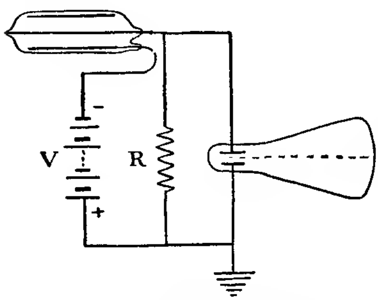

Fig. 6. The action of a counter is best studied with a cathode-ray oscillograph.

[6] Christoph, W., and Hanle, W., *Phys. Zeits.*, *34*, 641 (1933).
[7] Locher, G. L., *Frank. Inst., J.*, *216*, 553 (1933).

tential recovers itself according to the time constant R_1C of the circuit, C being the distributed capacity as well as the capacity of the coupling condenser.

The best way, however, to study the action of a G-M counter is to connect it directly to the two deflecting plates of a cathode-ray oscillograph as shown in Fig. 6. The other pair of oscillograph plates is connected to a linear sweep circuit whose frequency can be varied. If R is about 10^9 ohms, then as the potential V is raised, a point is reached at which deflections of the electron beam will occur at random intervals of time, indicating that the G-M tube has started to count. As V is raised farther, the average number of pulses per unit time remains the same, but the magnitude, as shown by the oscillograph, increases by nearly the same amount that V increases. By such means it can be shown that the potential to which the voltage falls during a discharge is not far below the threshold, the actual amount being roughly proportional to the difference between the applied voltage and the threshold potential.

The character of the discharge should be that shown in Fig. 7(a), where V_T is the threshold voltage. Counters

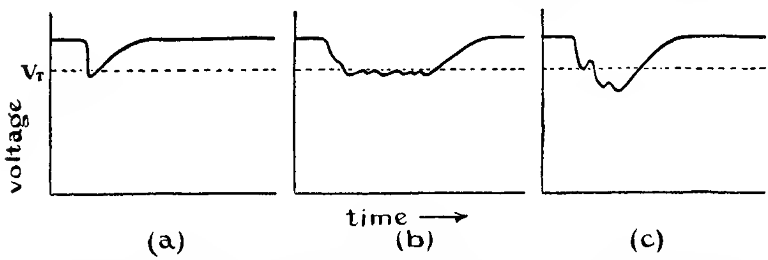

Fig. 7. Three typical discharges of a G-M counter as seen with the oscillograph. (a) represents the shape of discharge shown by a *fast* counter; (b) and (c) are representative of *slow* counters. The width of the pulse in (a) may be made as short as 10^{-6} second; that for (b) or (c) may be as long as 0.2 second for a very slow counter.

may be divided into two main classes, "fast" counters and "slow" counters. The drop in potential across the counter is extremely rapid for a fast counter, while the recovery time depends upon the product of R and the distributed capacity

of the circuit. If the counter is a slow one, the breakdown will be much less rapid, and the potential may remain near the threshold for a relatively long time, as much as 0.2 second in some cases, as represented in Fig. 7(b). When a radioactive source is brought up, the time spent by the counter in a continuous discharge state near the threshold may increase, so that the counter in a recording circuit would appear to be insensitive to radioactivity or even to have a negative sensitivity. In some cases the shape of the discharge is that shown in Fig. 7(c), where the breakdown is rapid at first but the counter fails to recover immediately, the potential fluctuating over wide ranges until recovery finally sets in.

Fast counters will retain the shape of discharge curve shown in Fig. 7(a) when the resistance R is decreased to as low as 10^5 ohms. The length of the pulse in this case will be about 10^{-5} second. The best counters will still extinguish themselves when R is made as low as 4000 ohms. The width of the pulse on the oscillograph in this case cannot easily be measured, but it should be less than 10^{-6} second if C is about 25 micro-microfarads.

Counters with this short time constant have important applications when high counting rates are to be measured or when the number of accidentals in a coincidence circuit is to be kept at a minimum. In fact, it is usually necessary to use only two G-M counters in a coincidence circuit, for, as will be shown later, if each of the two counters counts on the average 3 times a second, then with a pulse of time width 10^{-5} second there will be an average of only 16 accidentals per day.

A complete explanation of the action of these counters cannot be given, but it appears that the chief agents causing the pulse are electrons and not negative ions, since the latter have much too low a mobility to be collected in these short times. In a slow counter there is a delaying action of some sort, and charges are collected over a relatively long period of time. It seems probable that negative ions as well as electrons are collected at the central wire in this case.

As will be discussed presently, the surface of the cylinder has a vital effect upon the action of the counter. Among the possible physical properties which might be altered by treatment and affect the counter action could be mentioned (1) the work function of the surface, which would affect its photoelectric properties, and (2) the electrical resistance of the surface of the metal cylinder. At the present time, as already mentioned, very little is known of counter action.

Something can be said, however, as to the treatment which will give counters the very desirable characteristic of furnishing an extremely short pulse. This treatment, which will be discussed later, is not always necessary. In fact, counters with copper cylinders which have never been treated have worked well with 10^5 ohms across them. There is, at present, no rule by which it can be predicted whether or not a counter will have this short reaction time. The proper procedure is to try the counter in a circuit such as that shown in Fig. 13. If it fails to work, then an oscillograph would show that when a potential slightly above the threshold is reached, the counter will discharge once and then remain in a continuously conducting state.

Construction of G-M counters. The simplest method of making a G-M tube is to take a copper or brass tube of a

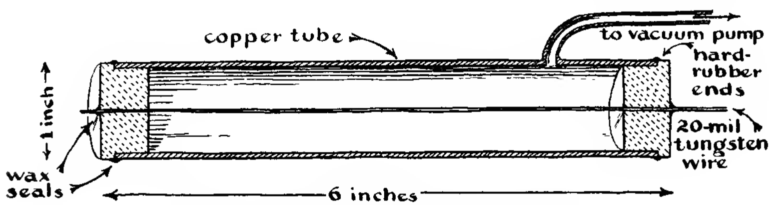

Fig. 8. Simple construction of a G-M counter.

length at least five times the diameter, insert a hard-rubber plug in each end, and pass through the plugs, coaxial with the cylinder, a straight wire 0.1 to 0.2 mm in diameter. (See Fig. 8.) The wire can be made of many metals, but tungsten or copper will give good results. The whole must be made tight and the gas pressure reduced to from 3 to 6 cm

of mercury. The gas may be air or a mixture of air and one of the noble gases, particularly argon.

A counter made in this fashion may work satisfactorily for a while, but it is not suited for constant operation over long periods of time. Even though the tube could be made perfectly tight, which is difficult, it still suffers from the defect of having a high temperature coefficient. Curtiss[8] has shown that with a tube having hard-rubber ends, the count goes down as the temperature increases, indicating an increase in the density of the gas, probably due to the outgassing of the hard rubber. This temperature coefficient can, in practice, be completely eliminated by sealing the

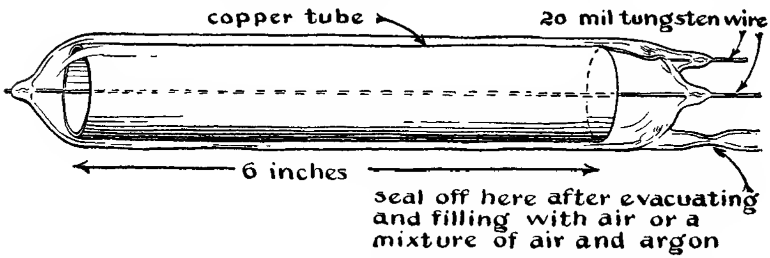

Fig. 9. Typical construction of a copper-in-glass counter. Following this general design, counters have been made from 0.5 cm to 10 cm in diameter.

metal tube inside a glass tube and making metal-glass seals to the tungsten wires. The construction details of a counter of this latter design are shown in Fig. 9. Satisfactory counters of this copper-in-glass type have been made from 0.5 cm to 10 cm in diameter.

After the counter is assembled, a concentrated solution of nitric acid (12 to 16 normal) should be admitted and allowed to attack the copper vigorously for 10 to 20 seconds. The acid is then removed and the counter washed thoroughly with distilled water. Under this treatment the copper will turn a dark, almost black color, which probably is due to a thin layer of CuO. The tube is then dried, evacuated, and the desired amount of gas admitted.

[8] Curtiss, L. F., *Bureau of Standards, J. of Research, 10,* 229 (1933).

The kind and amount of gas used determine to some extent the action of the counter. For many purposes air admitted to a pressure of 3 to 6 cm of mercury results in a very satisfactory counter. A mixture of argon and 10 to 20 per cent air for the same total pressure will have a threshold perhaps 40 per cent lower than air alone. There seems to be little choice, however, between the mixture of air and argon and air only. The counter will not work with pure argon. The threshold potential for a counter, 2.5 cm in diameter with a 10-mil wire, filled with 5 cm of mercury pressure of argon and 1 cm of air, will be about 800 volts. The same counter filled with air to the same total pressure will have a threshold of about 1200 volts.

Counters made according to the above directions will, in general, be of the *slow* type, that is, the collection time for the ions will be of the order of 0.1 to 0.01 second. Such counters are quite satisfactory for many purposes where short reaction times are not necessary. They may be used in the conventional Geiger circuit shown in Fig. 12, or if it is desired to eliminate the high resistance, a radio tube may be used to help the counter recover itself as shown in Figs. 14 and 15.

In case it is desired to make a *fast* counter, that is, one in which the collection time of the ions is of the order of 10^{-5} second, a different treatment of the copper cylinder is necessary. The treatment to be described is one of several known to produce a fast counter. A counter so treated will have the following characteristics: (1) The threshold potential will be as low or lower than for the same size counter filled with a mixture of argon and air at the same pressure. (2) The length of the plateau will be at least 30 per cent of the threshold potential. (3) The counter will function in the circuit shown in Fig. 13 with only 100,000 ohms in series with the high potential, instead of the 10^9 ohms necessary for a slow counter. (4) The efficiency is high. By amplifying the pulses, the efficiency of a $2\frac{3}{4}$-inch counter was found to be 100 per cent at a counting rate of 30,000 per

minute within the limits of experimental error, which may be taken to be 1 per cent.

The procedure to make a *fast* counter is as follows:

1. Starting with a copper-in-glass counter with a tungsten wire, clean the copper thoroughly with about 6 normal nitric acid. (A water aspirator is indispensable for admitting and removing solutions.) Such a concentration of acid will leave the copper very bright.
2. After rinsing well, introduce a solution of 0.1 normal nitric acid. This will remove any copper compounds formed by the stronger acid.
3. Rinse thoroughly (at least 10 times) with distilled water and dry.
4. With dry air inside, heat the whole counter in a large flame until the copper turns a uniform brownish-black color.
5. Seal the counter off temporarily and then heat for several hours at about 400°C. Upon cooling, the copper cylinder will be coated with the bright red oxide, Cu_2O.
6. Evacuate and admit dry NO_2 gas to a pressure of 1 atmosphere. (This gas can be made by the action of 16 normal nitric acid on copper. It may be dried by passing through $CaCl_2$ and P_2O_5.)
7. Heat the counter with the NO_2 until the Cu_2O turns a dark velvety color.
8. Admit argon (commercial, 99 per cent pure is satisfactory), which has been bubbled through xylene, to a pressure of 6 to 10 cm of mercury pressure. The counter should be tried at this point. For a 1-inch counter the threshold should be 600 to 800 volts for 8 cm of mercury pressure. If the counter does not work properly, the gas should be pumped out and more argon, which has been bubbled through the xylene, admitted.
9. When the counter is found to work satisfactorily, it may be sealed off.

Although all the above steps may not be necessary in all cases, yet this procedure has been found to give very

satisfactory counters having reaction times of 10^{-5} second or better. The characteristics of the counters also seem to be permanent. The photoelectric properties as well as the electrical resistance of the surface are probably radically changed by this treatment.

The use of a cathode-ray oscillograph is indispensable in the proper study of the action of a counter, and its use cannot be too strongly recommended.

The above treatment is limited to copper-in-glass counters, and no method as yet has been found to be applicable to counters in general.

Sensitivity of counters to ionizing particles. If a set of three identical counters are arranged one above the other, with their axes parallel and horizontal, and are connected to a circuit (see page 290) which responds only to coincidences between the three counters, then if the middle one is moved out of line, as shown in Fig. 10(a), the counting rate will begin to fall and, except for accidentals, which produce a small effect, the rate becomes zero when the middle one has been moved far enough so that a single particle cannot pass through all three. (The counting, when the three are in a line, is due, of course, to cosmic-ray particles passing through the three counters.) Comparing this rate with the rate due to double coincidences between the two outside counters, Street and Woodward[9] have shown that for counters 3.82 cm in diameter the effective diameter is the same as the geometrical diameter. Similarly, by rotating the middle counter 90°, as shown in Fig. 10(b), and moving it parallel to its axis, the sensitivity along the counter can be obtained. With the conditions under which they were

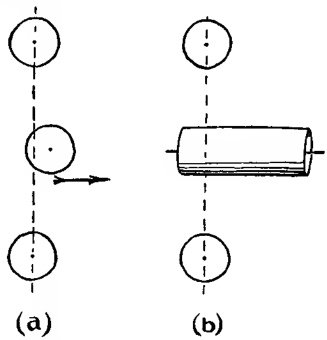

Fig. 10. Testing the sensitivity of different regions of a counter.

[9] Street, J. C., and Woodward, R. H., *Phys. Rev.*, *46*, 1032 (1934).

operating and with a counter whose geometrical length was 13 cm, the effective length was found to be 10.5 cm. The difference is probably dependent on the geometry of the arrangement as well as the potentials used.

A set of G-M tubes arranged in a vertical line and connected to count coincidences provides a means of determining the efficiency of a counter. If the middle counter were 100 per cent efficient, that is, if it responded to all cosmic-ray particles passing through the outside counters, then, if proper allowance were made for the accidentals, there should be as many counts when the middle one is turned off as when it is turned on. (The counter should not actually be removed, since the amount of absorbing matter will then be changed.) By comparing the rates in the two cases, an actual measure of the efficiency can be obtained. A good counter should be at least 95 per cent efficient. It is important that the efficiency for counters in a coincidence circuit be high, or the number of counts will be greatly reduced. If the efficiency of each of n counters is ϵ, the number of coincidences will be only ϵ^n of the number which would be counted if they were 100 per cent efficient.

G-M tubes for special uses. The tube illustrated in Fig. 9 answers very well the needs for work on cosmic rays, since the radiation readily penetrates the thin walls. For other types of radiation special constructions are necessary or are more efficient. A few of these will be discussed briefly.

For β-ray measurements, a point counter, as discussed on page 259, can be used at atmospheric pressure, in which case no trouble is experienced by the particles in entering the counter. In case the cylindrical counter is preferred, there are two alternatives: (1) Construct a thin window in the counter, usually at one end, or (2) if the β-ray source can be placed in a large chamber where the pressure can be reduced to the operating pressure of the counter, the metal cathode of the counter can be made of very thin material. As an illustration of this latter method Smythe and Hemmendinger[10]

[10] Smythe, W. R., and Hemmendinger, A., *Phys. Rev.*, *51*, 178 (1937).

have measured the activity of the potassium 40 isotope by using a counter with an aluminum wall 0.0254 mm thick and letting air at 5.6 cm of mercury pressure into the whole apparatus after the sample of potassium had been collected.

The above procedure for β rays applies equally well to α rays or other heavy charged particles, except that in general the windows must be made of thinner material, owing to the high energy loss of these particles in passing through matter. However, the proportional counter (see page 260) or the linear amplifier of Wynn-Williams,[11] as developed by Dunning,[12] is usually preferable in detecting these heavy particles, since the effects of other ionizing agents are negligible.

For the detection of γ rays it is desirable to increase as much as possible the number of secondary electrons emitted from the walls of the metal tube under the action of the radiation. As pointed out by Evans and Mugele,[13] this sensitivity can be increased by (1) making the cathode material from one of the heavy elements, such as platinum, which increases the absorption of the γ rays in the walls and produces more secondary electrons, and (2) increasing the surface area of the metal forming the cylinder either by grooving or by using a fine mesh screen. By these two devices it is possible to increase the count by a factor of two over that given by a plain copper electrode. The usefulness of a counter for measuring radiations is illustrated by the work of Pohl and Faessler,[14] who have shown that the intensity of a certain AgK_β radiation required only a few minutes to get a measurable response with a G-M counter, whereas it was necessary to expose Laue X-ray film to the same radiation for 100 hours.

When light of the proper frequency falls upon the inside of the metal tube of a counter, photoelectrons are liberated. Such a G-M photoelectric cell becomes a means of detecting

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[11] Wynn-Williams, C. E., *Roy. Soc., Proc., A, 131*, 391 (1931).
[12] Dunning, John R., *Rev. Sci. Instruments, 5*, 387 (1934).
[13] Evans, R. D., and Mugele, R. A., *Rev. Sci. Instruments, 7*, 441 (1936).
[14] Pohl, M., and Faessler, A., *Zeits. f. Physik, 102*, 562 (1936).

very feeble radiations. The metal used for the cylinder in the ordinary counter has its photoelectric threshold below the region of transmission by the glass and hence does not respond to the light falling upon it. For metals of this nature the tube may be made to respond to radiations from 1800 Å up to the threshold of the metal by cementing a quartz window on one end of the glass tube as shown in Fig. 11. The central wire of tungsten should be large enough

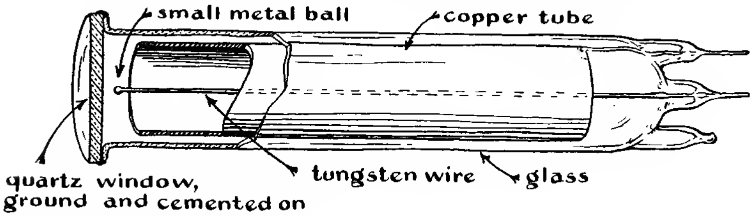


Fig. 11. A counter which may be used for photoelectric work.

to support itself well from one end. The free end should terminate in a small ball to eliminate point discharges.

The whole tube surrounding the metal cylinder could be made from quartz, and quartz-glass graded seals used where the wires are to be taken through.

The spectral sensitivity characteristics of counters having aluminum, zinc, cadmium, iron, and copper cathodes have been determined by Kreuchen[15] in the region 4000 Å to 2540 Å. He found that they correspond in all cases for the same metals when used in ordinary photoelectric cells. Using the three metals zinc, cadmium, and copper in the bulk state, Kreuchen[16] also found that the sensitivity was increased by activating with hydrogen, but that these metals when evaporated showed no increase when treated with hydrogen. The photoelectric yield of the activated bulk metal and the evaporated metal was the same.

Very little work has so far been done with cathodes of metals that are sensitive in the visible. Locher[17] was one

[15] Kreuchen, K. H., *Zeits. f. Physik*, *94*, 549 (1935).
[16] Kreuchen, K. H., *Zeits. f. Physik*, *97*, 625 (1935).
[17] Locher, G. L., *Phys. Rev.*, *42*, 525 (1932).

of the first to work on this problem, producing counters with cylinders of various metals. He tested the sensitivities in the ultraviolet and in the visible, both of the pure metals and metals coated with dyes and other foreign substances. Kolin[18] has succeeded in evaporating sodium, magnesium, and calcium onto the metal cylinder and has attained high sensitivities in the visible. Christoph[19] has done the most extensive investigation of the problem so far. Using an evaporated coating of calcium, he has determined the characteristic of the counter for ultraviolet and visible light and finds that consistent behavior can be obtained after the counter has had a chance to age.

It appears that photoelectric G-M counters are less reliable than the photoelectric cell at the present time, but, owing to the sensitivity attainable, the former may offer a fruitful field of research.

Methods of measuring the number of counts. The string electrometer has been applied successfully by Rutherford and others[20] in counting particles up to an average of 1000 per minute by recording the motion of the fiber on a photographic film. This method has the advantage of simplicity but is limited to relatively low counts because of the response of the electrometer. It also has the disadvantage that the reading cannot be obtained immediately. The usual method today is to take advantage of the amplifying action of various kinds of vacuum and gas tubes, which eventually operate a mechanical recorder.

The conventional circuit for such a recorder in its simplest form is shown in Fig. 12. The bias on the grid of the first tube is such that the plate current is only partially stopped. The bias on the second tube is such that it almost completely blocks the plate current. When an ionizing particle passes through the counter, the wire collects a negative charge, which causes the grid of T_1 to go negative. The plate poten-

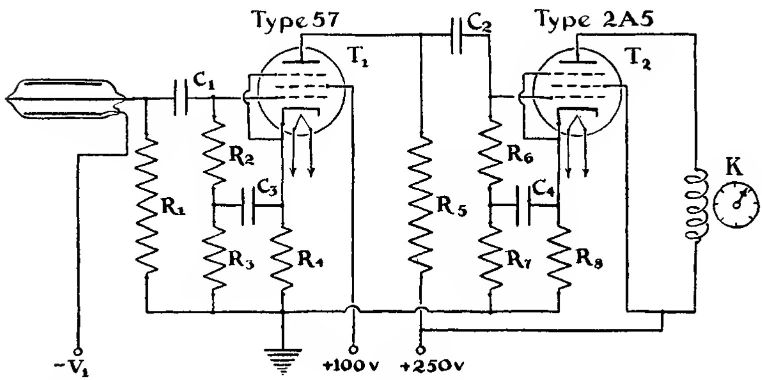
[18] Kolin, A., *Rev. Sci. Instruments*, *6*, 230 (1935).

[19] Christoph, W., *Ann. d. Physik*, *23*, 47 (1935).

[20] Rutherford, Ernest; Chadwick, James; and Ellis, C. D., *Radiation from Radioactive Substances*, page 52. New York: The Macmillan Company, 1930.

tial of T_1 rises, thus causing the grid on T_2 to go positive. T_2 then passes current, and if the quantity of charge is sufficient, the mechanical recorder[21] K will be actuated.

The value that R must have for the counter to function properly will depend on the counter. For a very slow counter, that is, one which requires a long time for the charges to be collected, it may be necessary for R_1 to be as



R_1 = 0.5 to 5 × 10^9 ohms
R_2 = 5 × 10^6 ohms
R_3 = 0.5 × 10^6 ohms
R_4 = 3000 ohms
R_5 = 10^5 ohms
R_6 = 2 × 10^3 ohms
R_7 = 10^5 ohms

R_8 = 2000 ohms
C_1 = 30 to 50 $\mu\mu$f
C_2 = 10^{-3} μf
C_3 = C_4 = 0.1 μf for low voltage
K = high-impedance mechanical recorder
V_1 = counter threshold + 100 v

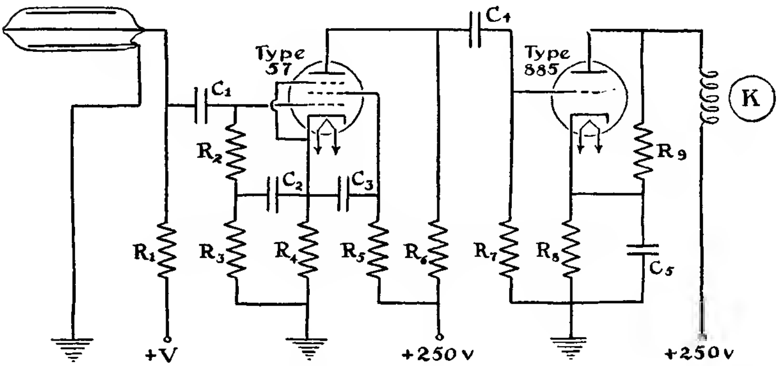
Fig. 12. A conventional circuit for recording the pulses delivered by a G-M counter.

high as 5×10^9 ohms. If the counter is a fast one, that is, if it is capable of giving a pulse of short duration, then R_1 may be as low as 10^5 ohms, and in some cases may be dropped to 4×10^3 ohms. For these short reaction times, the duration of the pulse passed on to the second tube is too short for a vacuum-type tube, such as the 2A5, to pass sufficient quantity of electricity to actuate the mechanical recorder, and it is necessary to use either a pulse-lengthening device such as the multivibrator circuit to be described later, or

[21] Mechanical recorders of various resistances are manufactured by the Central Scientific Company, Chicago, Illinois.

a gas tube, for example, the 885. A circuit that is self-biasing throughout and designed for a fast counter using the 885 is shown in Fig. 13. The action of the second half of this circuit will be described later.

Almost any counter can be made to count by using a vacuum tube such as the type 57 or 6C6[22] to help the G-M counter extinguish itself. By so doing, it is possible to



$R_1 = R_2 = R_3 = R_6 = R_7 = 10^5$ ohms
$R_4 = 2000$ ohms
$R_5 = 4 \times 10^5$ ohms
$R_8 = 10^4$ ohms
$R_9 = 7.5 \times 10^4$ ohms
$C_1 = 50\ \mu\mu f$
$C_2 = C_3 = 0.1\ \mu f$
$C_4 = 10^{-4}\ \mu f$
$C_5 = 0.2$ to $1.0\ \mu f$
K = high-impedance mechanical recorder
V = counter threshold plus 100 volts

Fig. 13. A circuit designed for use with a *fast* counter. The resistance in series with the counter is much lower than in the conventional circuit. Because of the short pulse, a trigger-type tube is used to actuate the recorder.

eliminate such a high resistance as is used in the conventional circuit as well as greatly to increase the efficiency at high counting rates. There are several types of circuits by which this may be accomplished. The first[23] is shown in Fig. 14. The cylinder of the counter is connected directly to the grid of the first tube, while the potential which is applied to the wire is also connected to the plate of the tube through a

[22] The grid potential–plate current characteristic of these tubes makes them very desirable for this type of work. A negative $4\frac{1}{2}$ volts on the control grid are sufficient to block a potential of 1500 volts on the plate if 45 volts are used on the screen grid.

[23] Neher, H. V., and Harper, W. W., *Phys. Rev.*, *49*, 940 (1936).

resistance R_2. The coupling to the next tube is made by the usual condenser, except that in this case the pulse delivered is large enough to permit a small capacity C of the order of 10^{-5} microfarad to be used instead of 10^{-3} to 10^{-4} microfarad, as is used for the coupling condenser in the conventional circuit.

The action of the circuit can be explained briefly as follows: The vacuum tube is biased close to the point at which very little plate current flows. The full potential of V_1 is then across both the tube and the counter. When an ionizing

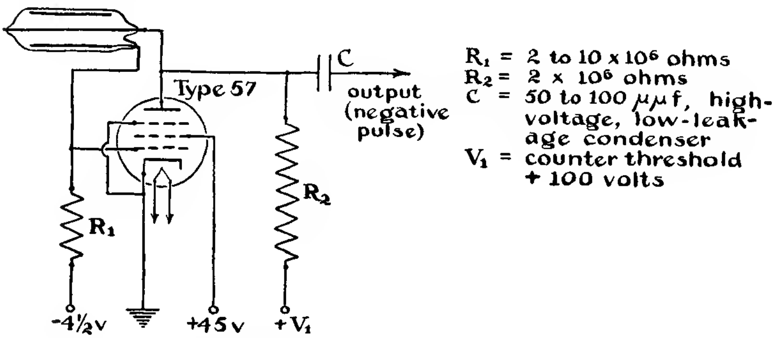


Fig. 14. A circuit for use with a slow or fast counter using low resistances. The radio tube helps the G-M counter extinguish itself.

particle passes through the counter, positive charges collected by the cylinder cause the grid to go less negative. A current flows, causing a drop in potential across R_2. When this drop becomes sufficient, the discharge in the counter will be extinguished, and the circuit recovers itself. This recovery is very rapid because of the low values of capacity and resistance. With such a circuit it has been found possible to count random pulses of 10^5 per minute with apparently few being missed.

The pulse delivered to a second tube will be negative, which means that the plate current in this tube must flow continuously except when a pulse occurs. If it is desired to operate a power tube, then, in order to conserve power, it is best to use another tube such as a type 27 inserted between

T_1 and T_2 to reverse the direction of the pulse. The negative pulse delivered by this circuit is, however, just what is wanted on the mixing tubes in case two or more counters are connected to count coincidences.

Another method[24] of using a vacuum tube to help the G-M counter to recover itself is shown in Fig. 15. It will be noticed that no bias is used on the grid, so that there is normally a drop of only a few volts through the tube. Thus the cathode, grid resistance, screen voltage supply, and so forth, are all at a high positive potential. This puts a high positive potential on the wire of the G-M counter. If this potential is above the threshold value, then when an ionizing particle passes through the counter, a negative charge collects on the grid, blocking off the current in the tube. This allows the cathode, grid, and so forth, to drop rapidly toward ground potential. As soon as the potential across the counter drops below the threshold value and the negative charges have flowed off across R_1, however, the grid again takes control, and the circuit rapidly recovers itself and is ready for another count.

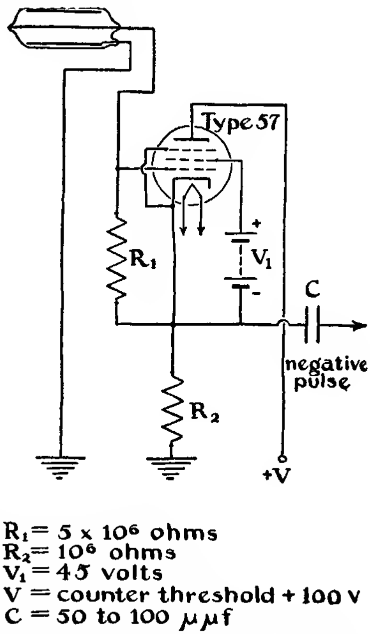
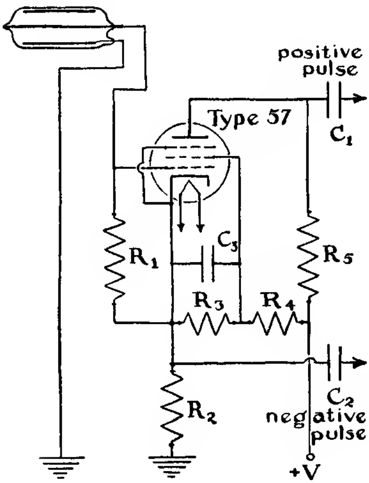


Fig. 15. Second method of using a radio tube to help the counter extinguish itself. Since there is no bias on the grid of the tube, practically the full voltage, V, is across R_2 and hence also across the counter.

It will be observed that the pulse taken from the circuit of Fig. 15 is negative. If a positive pulse is desired, a resistance of perhaps 2×10^5 ohms may be placed in the plate circuit and a positive pulse to the next stage taken off as

[24] Neher, H. V., and Pickering, W. H., *Phys. Rev.*, *53*, 316 (1938).

shown in Fig. 16. If, in addition, it is desired to climinate the screen supply battery, a bleeder may be used as is also shown in Fig. 16. When this resistance is placed between the high-voltage supply and the cathodc, there is a definite end to the plateau, owing to the fact that the potential across the counter cannot drop below a certain value, which is determined by the ratio R_4/R_2. Consequently, if the high voltage is raised to such a point that this minimum value is above the threshold, the counter will not extinguish itself.



$R_1 = 5 \times 10^6$ ohms
$R_2 = 10^6$ ohms
$R_3 = 0.2 \times 10^6$ ohms
$R_4 = 0.5 \times 10^6$ ohms
$R_5 = 0.2 \times 10^6$ ohms
$C_1 = C_2 = 50$ to $100\,\mu\mu f$
$C_3 = 0.1\,\mu f$
V = counter threshold + 100v

Fig. 16. Self-biasing arrangement for the screen grid of the circuit in Fig. 15. A positive pulse may also be taken off when the resistance R_5 is inserted.

The advantages of this circuit over the preceding one are as follows: (1) The cylinder of the counter is grounded, which means that shielding is unnecessary and insulation less troublesome. (2) For large counters the reaction time is less, since only the capacity of the wire, which is small, plays a part. (3) Either a positive or a negative pulse may be taken off. (4) The potential across the radio tube is not so large. The disadvantages are as follows: (1) An insulated filament supply must be used. (2) The high-voltage supply must be able to stand from 0.5 to 1 milliampere of current continuously.

This latter circuit has been applied to some large counters for cosmic-ray work. Since the number of counts for a given solid angle subtended by counters counting coincidences goes up with the area of the counters, there is a de-

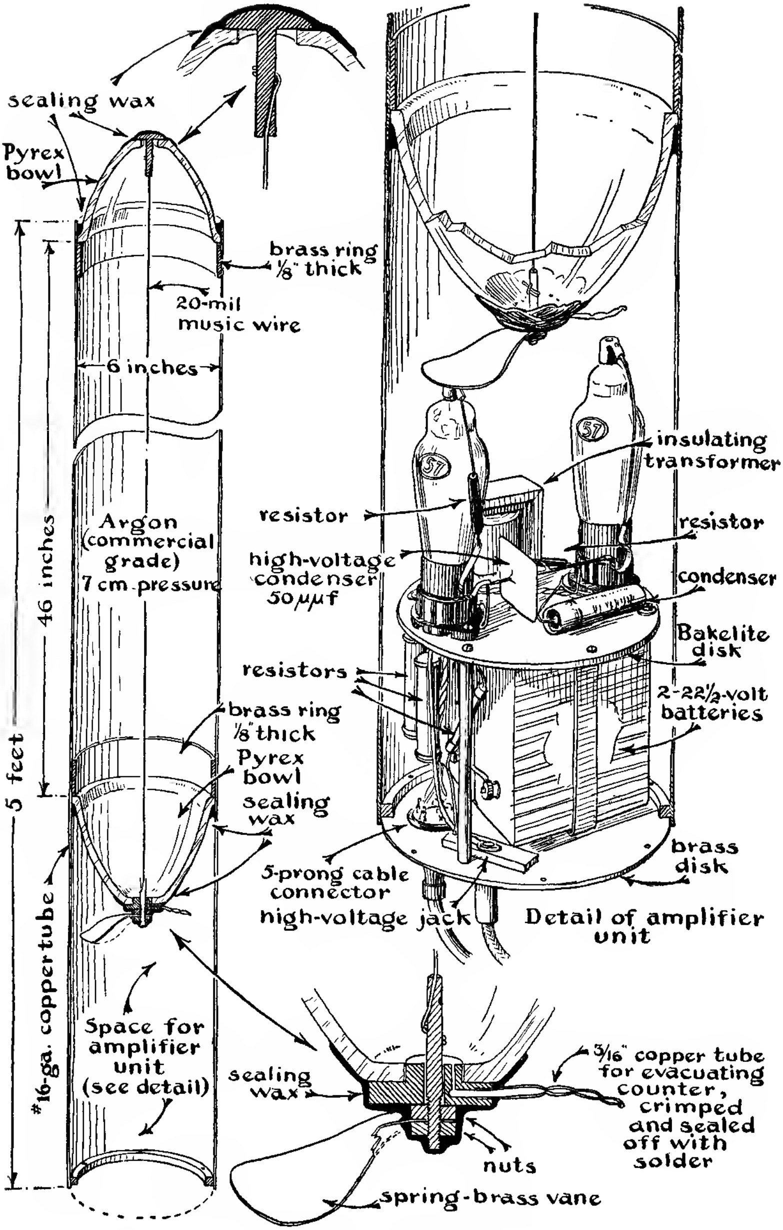


Fig. 17. Design of some large counters using the circuit shown in Fig. 15.

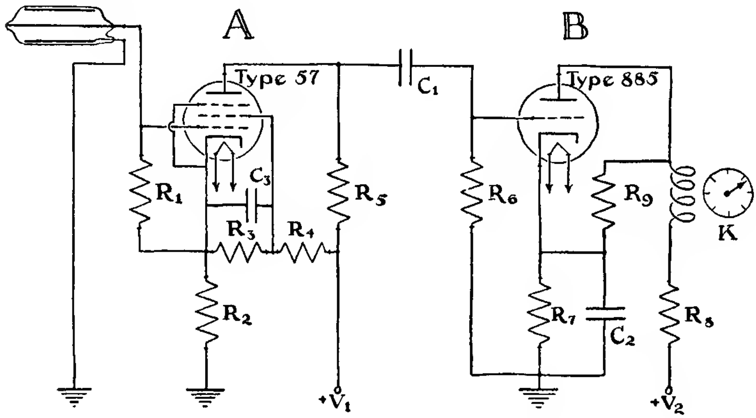
cided advantage in increasing the size of the counter tubes. In this instance, copper tubes 5 feet long with a $\frac{1}{16}$-inch wall were employed. Some 12 inches of space were used at one end to mount two of the radio tubes. The arrangement is shown in Fig. 17. The Pyrex bowls which seal the ends are commercial transmitting station lead-in bowls, with the edges ground to fit inside the 6-inch tubing. Commercial argon, 99 per cent pure, was used at a pressure of 7 cm of mercury. The counting rate of each counter, which is due to cosmic rays and radioactivity in the counter and surroundings, was about 100 per second. The resolving time was 2×10^{-5} second with the constants shown in Fig. 15. This means that with three counters separated in a horizontal plane the accidentals were about 5 per hour.

Because of the short duration of the pulse in the preceding circuits, it is sometimes difficult to operate a mechanical recorder by using an amplifying tube such as that shown in Fig. 12. It is much more satisfactory to use a gas-filled trigger-type tube, such as the argon type 884, 885, or a mercury-vapor thyratron.[25] The former are quite inexpensive, have a short de-ionization time, and are preferable to the latter. One of the most satisfactory methods for using this tube has been devised by Pickering.[26] It is shown in Fig. 13 and in Fig. 18B, in which the second type of extinguishing circuit described above feeds the recorder circuit. The grid of the 885 is self-biased to a little beyond the point at which it can keep control. When the positive pulse from circuit A causes the gas discharge to take place in the 885, current flows through the recorder K, causing it to record a count. As the current continues to flow, C_2

[25] Each of these tubes has a very low plate resistance when in the conducting state. If the grid is sufficiently negative, no plate current will flow, but as soon as the grid potential is raised beyond a certain point, a gaseous discharge occurs, and the grid loses complete control. If a resistance is in series with the plate, the drop in potential inside the tube becomes approximately the ionization potential of the gas, or about 17 volts in the case of the argon tubes. The discharge can be stopped by dropping the plate potential below the ionization potential of the gas for a few microseconds.

[26] Pickering, W. H., *Rev. Sci. Instruments*, *9*, 180 (1938).

charges up, and the potential of the cathode approaches that of the plate. However, the grid has remained near ground potential, so that the effective bias becomes very large. When it becomes large enough, and the drop of potential across the tube becomes sufficiently small, the gaseous discharge ceases, and the circuit returns to its normal state.



$R_1 = 5 \times 10^6$ ohms
$R_2 = 10^6$ ohms
$R_3 = R_4 = R_6 = 0.5 \times 10^6$ ohms
$R_5 = 0.25 \times 10^6$ ohms
$R_7 = 10^4$ ohms
$R_8 =$ current limiting resistance
$R_9 = 8 \times 10^4$ ohms

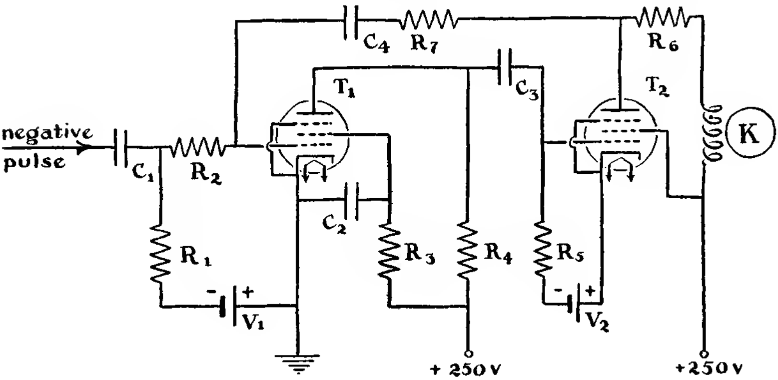
$C_1 = 50\ \mu\mu f$
$C_2 = 0.2\ \mu f$
$C_3 = 0.1\ \mu f$
$V_1 =$ counter threshold + 100v
$V_2 = 250$ volts
K = high-impedance mechanical recorder

Fig. 18. The circuit of Fig. 16 feeds a self-biased recording circuit.

The value of C_2 can be varied to suit the impedance of the recorder K. For the shortest resolving time, C_2 should be made as small as possible. The resistance R_8 may or may not be necessary, depending on the impedance of the recorder. In any case the instantaneous current through the 885 should not exceed 0.3 ampere. The resolving time of the circuit is usually shorter than that of the mechanical recorder.

Another method of producing a pulse of much longer duration than the initial pulse and so operating a mechanical recorder is with the so-called multivibrator circuit. This

circuit will give a square wave form in the output, the voltage swing of the plate being nearly the full potential applied. The length of the pulse on the output is independent of the length of pulse on the input, provided the latter is shorter than the natural pulse length delivered by the circuit.



Medium Power Output

T_1 = Type 6C6
T_2 = Type 41
$R_1 = R_2 = R_5 = 10^5$ ohms
$R_3 = 0.5 \times 10^6$ ohms
$R_4 = 6 \times 10^4$ ohms
$R_6 = 0$ to 1.5×10^4 ohms depending on recorder K
$R_7 = 10^6$ ohms
$C_1 = 10^{-3}$ to $10^{-4}\,\mu$fd
$C_2 = C_3 = 0.1\,\mu$fd, 400 volt
$C_4 = 10^{-2}$ to $10^{-4}\,\mu$fd (see text)
K = high-impedance mechanical recorder
V_1 = 3 volts
V_2 = 60 volts

Large Power Output

T_1 = Type 6A4
T_2 = Type 6L6
$R_1 = R_2 = 10^5$ ohms
$R_3 = 0$
$R_4 = 10^4$ ohms
$R_5 = 5 \times 10^4$ ohms
$R_6 = 0$ to 1000 ohms depending on recorder K
$R_7 = 10^6$ ohms
$C_1 = 10^{-3}$ to $10^{-4}\,\mu$fd
$C_2 = 0$
$C_3 = 0.5\,\mu$fd, 400 volt
$C_4 = 10^{-2}$ to $10^{-4}\,\mu$fd (see text)
K = low-impedance mechanical recorder
V_1 = 11 volts
V_2 = 45 volts

Fig. 19. Multivibrator circuit.

This natural pulse length is determined chiefly by the feedback capacity C_4, Fig. 19. The quantity of electricity which flows during a pulse is quite sufficient to operate a Cenco recorder of either the high- or low-impedance type. If the 6L6 is used in the second stage, as much as 0.3 to 0.4 ampere

can be delivered for any predetermined time up to say 0.1 second, provided the impedance of the output circuit is sufficiently low. In case this type of circuit is desired, instead of using a thyratron such as the type 885, the arrangement in Fig. 19 may be substituted directly for the two tubes in Fig. 13. It has many applications where a nonlinear, constant pulse size output is desired. By adjusting the grid voltage on the second tube the circuit can be made nonsensitive to input pulses less than a certain size. For all pulses with a voltage swing beyond this limiting value, the size of pulse in the output will be constant, provided the pulse length in the input is less than the natural pulse length of the output.

The behavior of the circuit may be described briefly as follows: T_1 is biased so that it acts as a linear amplifier. T_2 is biased to just beyond the cutoff. When a negative pulse arrives at C_1, T_1 passes a positive pulse onto T_2, and owing to the large condenser C_3, the grid of T_2 follows closely the plate of T_1 and hence goes positive by an amount depending on R_4 and the type of tube T_2. As the plate of T_2 drops in voltage, a negative pulse is passed back onto the grid of T_1, causing T_2 to become still more conducting. This process continues until the plate of the second tube has dropped to within a few volts of the potential of its cathode. The grid of T_1 is now far below the potential of its cathode, and the charge on C_4 must leak off across R_2. While this is occurring, T_2 is still highly conducting. When the grid of T_1 returns to a point where the first tube again begins to conduct current, the plate of T_2 is allowed to rise in potential, and this in turn causes T_1 to be still more conducting. The process is just the reverse of the initial stages of building up the pulse. The make and break of the current in the plate circuit of the second tube is extremely rapid, each appearing to consume less than 10^{-6} second, provided there is a pure resistance load. The time during which the plate current in T_2 remains at its constant value can be determined by C_4. As an illustration, when $C_4 = 2 \times 10^{-4}$ microfarad in either

of the circuits shown in Fig. 19, the length of pulse in the output is about 5×10^{-4} second when a pulse the length of which is 10^{-5} second is fed to the input.

When the bias of T_2 is lessened, there comes a point when the circuit will become unstable and oscillate. Just before this point is reached, the sensitivity becomes extremely high. The point at which oscillations begin depends on C_4—the larger C_4, the greater must be the bias voltage on T_2. Using a type 6C6 and a type 41, with $C_4 = 0.5 \times 10^{-4}$ microfarad and the other constants those given in Fig. 19, a 0.007-volt pulse input of 10^{-5} second duration results in a full voltage swing of the plate. This is a voltage amplification of about 2.5×10^4. For an output pulse of longer duration, for example, 10^{-2} second, C_4 must be about 10^{-3} microfarad. In this case, for stable operation, T_2 must be biased such that a 3- to 4-volt pulse is needed on the input.

The circuit is adaptable for use with either a *fast* or *slow* G-M counter. If used with a fast counter, the negative pulse from the wire of the counter can be fed onto the grid of T_1 directly or through the condenser C_1. In case a slow counter is used, Getting[27] has pointed out that such a multivibrator circuit can be made to extinguish the counter in a way similar to the action of the circuits in Figs. 14 and 15. For such operation the wire of the counter is connected directly to the grid of T_1 with $R_2 = 0$ and $R_1 = 4 \times 10^6$ ohms. The cylinder of the counter has a negative potential applied equal to the threshold voltage plus 100 volts. The value of C_4 is adjusted to the reaction time of the individual counter as well as the reaction time of the recorder. A value of 3×10^{-4} microfarad is an average. The length of the plateau, however, is limited to the voltage swing of the output tube.

If the counts per unit time become too large, the mechanical recorder will miss an appreciable number. It is shown on page 299 that if any device can respond to only those impulses separated by a time interval greater than τ, then

[27] Getting, I. A., *Phys. Rev.*, *53*, 103 (1938).

the relative number of pulses missed, if they are spaced at random in time, is τN, where N is the average number of pulses per unit time. To overcome this difficulty, Wynn-Williams[28] has devised a scale-of-two circuit which cuts down the number of pulses by a factor of just two. It consists of two tubes such as the type 885, each tube being discharged by every other pulse. If another scale-of-two circuit is connected to one of the tubes of the first circuit, each tube of the second will respond alternately to half of the original pulses. Thus, one tube of the second circuit responds to only one fourth of the original number of pulses. This process of adding more scale-of-two circuits may be continued indefinitely, with one tube of the final circuit counting 2^{-n} of the original pulses, where n is the number of scale-of-two circuits.

A diagram of a modified[29] set of two of these scale-of-two circuits is shown in Fig. 20. The action is as follows: Let tubes 3 and 6 have a gaseous discharge. This state of affairs can be obtained by first closing S_1 and then S_2. The current through tubes 3 and 6 will cause a drop in potential across R_2 and R_4, which will bias tubes 2 and 5 so that they will not glow when S_2 is closed. The ratio of the plate potential to the grid potential for the grid to keep control is about 10 to 1 for the type 885 tube. However, to secure consistent action it is best to have this ratio somewhat lower. Ratios from 5 to 1 to 8 to 1 are recommended. Let a negative pulse be delivered to tube 1. A positive pulse will be passed on to tubes 2 and 3. Tube 2 will then become conducting, the drop in potential from plate to cathode becoming the ionization potential of the argon, or about 17 volts. The discharge of tube 2 thus causes a sudden drop in potential across R_8 which is passed on through C_4 to the plate of tube 3. But since tube 3 was conducting, R_9 already had a large drop in potential across it, and the additional pulse passed on

[28] Wynn-Williams, C. E., *Roy. Soc., Proc.*, *136*, 312 (1932).

[29] Shepherd, William G., and Haxby, Robert O., *Rev. Sci. Instruments*, *7*, 425 (1936).

through C_4 makes the plate of tube 3 go negative with respect to the cathode. The discharge is extinguished, and its grid then takes control. Tube 2 is now glowing, and tube 3 is in the nonconducting state. When a second negative pulse arrives at C_1, the above procedure is just the same except

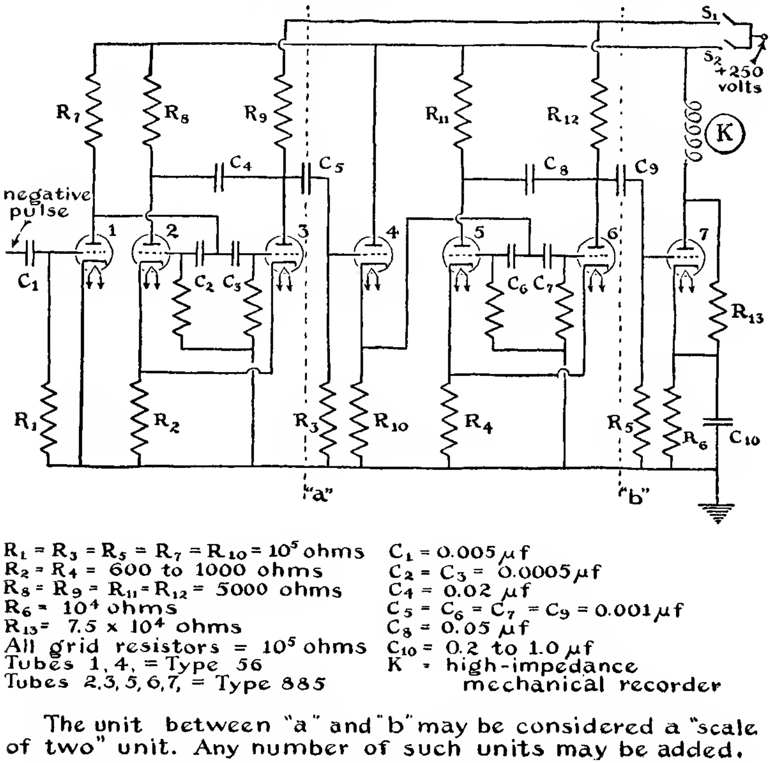


Fig. 20. Modified Wynn-Williams scale-of-four working into the recording unit B of Fig. 18.

that the tubes are reversed. It is obvious, then, that C_5 will receive a positive pulse only when tube 3 is made non-conducting, which will be just half the number of times a negative pulse arrives at C_1.

The unit from "a" to "b" of Fig. 20 is the same as the unit composed of tubes 1, 2, and 3, except for a slight difference in circuit constants and in the action of tube 4. This latter

tube is inverted, so that it passes on a positive pulse as well as responds to a positive pulse but is relatively insensitive to negative pulses. The number of pulses which appear at C_9 is then only one fourth of the number impressed on C_1. The unit from (a) to (b) may be considered a scale-of-two unit, and any number may be added. The final output is made to actuate a self-biased recording circuit as shown in Fig. 18B.

Tubes 1 and 4 act as one-way valves, keeping negative pulses from passing through. This makes for more consistent action, since a large negative potential applied to the grid of an 885 will sometimes cause it to extinguish. To maintain stability, it is necessary to have the time constant of the plate circuit greater than that of the grid circuit.

Still another method is available for counting impulses delivered at a high rate. By using a circuit somewhat similar to the scale-of-two, Hunt[30] has devised a scheme to obtain a pulsating direct current derived from charging and discharging condensers by means of type 885 tubes. A micro- or milliammeter gives a reading proportional to the average rate of arrival of the pulses. By choosing the proper capacities and resistances, this direct-frequency meter can be used in counting random pulses up to 10^5 per minute. The apparatus is conveniently calibrated with a beat-frequency oscillator.

Coincident circuits. In cosmic-ray work especially, it is desirable to record only simultaneous discharges of two or more counters. Several means have been devised for accomplishing this, but the one now in almost universal use is that of Rossi.[31] It may be applied to any number of counters. The circuit is shown in Fig. 21. The principle of operation is as follows: The plates of all tubes are connected in parallel across a high resistance R_4 and a source of potential. The grid of each tube is normally at the same potential as the cathode, so that the drop in potential

[30] Hunt, Frederick V., *Rev. Sci. Instruments*, *6*, 43 (1935).
[31] Rossi, B., *Nature*, *125*, 636 (1930).

across any one in the static condition is small compared with the drop across R_4. Under these conditions, if a negative pulse arrives at C_1, tube T_1 will instantaneously have a much higher resistance. However, since T_2 and T_3 are in parallel with T_1, there will be very little effect on the current through R_4, and hence the drop in potential across R_4 will be practically unaltered. The same holds if two tubes are affected, say T_1 and T_2, for even though these suddenly assume a high resistance due to their grids simultaneously being made more

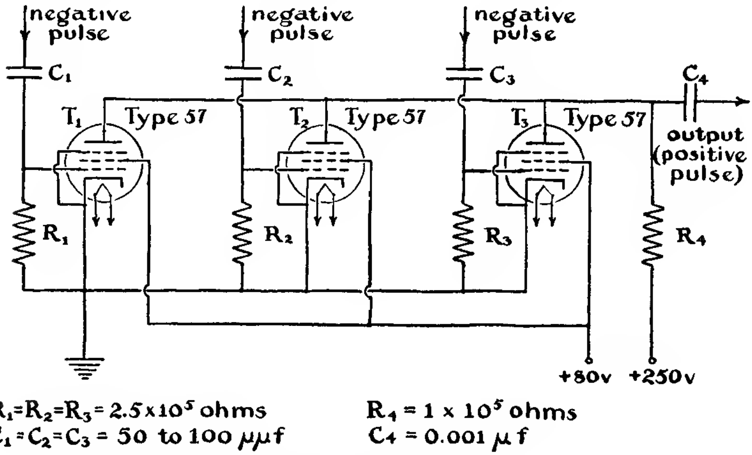


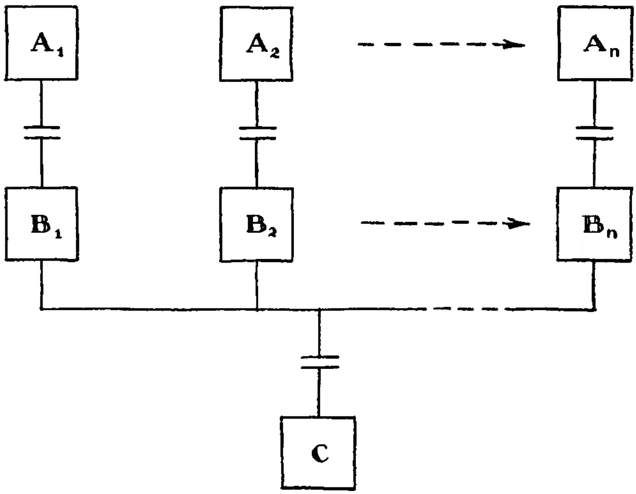
Fig. 21. Coincidence circuit of Rossi. Any number of tubes may be used in this parallel arrangement.

negative, the third one still has a low resistance compared with R_4, and the resultant effect passed on through C_4 will still be small. However, if all three grids go more negative simultaneously, then the potential at C_4 rises, and a positive pulse is passed to the output.

With the circuit constants given in Fig. 21 the direct-current resistance of each of the 57 or 6C6 tubes is 4000 ohms. The maximum possible voltage change to the output when one tube only receives a negative pulse is 0.8 volt, and when two tubes only are so affected, the maximum possible change is 2.8 volts. However, when the grids of all three tubes go negative simultaneously, the maximum change can be as

large as several hundred volts. By suitable adjustment of C_4, or of the grid potential on the first tube in the output, it is easy to rule out completely the singles and doubles and record only the triples.

For cosmic-ray work in which doubles, triples, quadruples, or any other number of coincidences are to be recorded, the



$A_1 = A_2 = A_n =$ G-M tube connected with vacuum tube as shown in Figs. 13, 14 or 15
$B_1 = B_2 = B_n =$ Amplifying tube such as shown in Fig. 21
C = Suitable mixing tube such as is shown in Fig. 18B

Fig. 22. Schematic diagram for any number of G-M counters arranged to count coincidences.

following assembly, shown diagrammatically in Fig. 22, can be recommended:

1. Use the required number of high-speed counting circuits shown in Figs. 13, 14, or 15.
2. Connect the outputs through a capacity to the grids of the coincidence tubes shown in Fig. 21.
3. Use the output of this coincident circuit to operate the circuit shown in Fig. 18B.

High-voltage sources. Although batteries furnish an ideal source of high potential for counters, the expense involved usually prohibits their use. High-voltage direct-current generators can also be used, but the actual power required for the operation of a counter is so small that here again the expense is unjustified. The simplest and most practical method is to rectify alternating current after the potential has been increased with a transformer to the desired voltage, and then smooth the pulsating output with a condenser or, if much current is to be drawn, with one or more condensers and chokes.

In most cases half-wave rectification is sufficient, since the actual current drain for a Geiger counter is usually small.

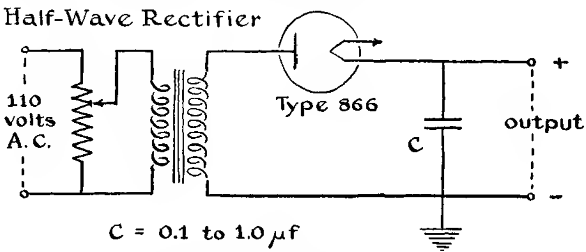


Fig. 23. For many purposes where the current drain is small, half-wave rectification is sufficient.

A simple, inexpensive rectifier is shown in Fig. 23, where a type 866 mercury-vapor tube[32] allows the condenser, C, to charge up to the peak voltage supplied by the transformer. It is necessary to have a filament transformer capable of withstanding the required potential if the negative side is grounded. The condenser C also has across it the full output potential. Its capacity need be no larger than 0.1 microfarad if only current to supply the counter is drawn. The amount of ripple for a current I can be computed approximately from

$$\Delta V = \frac{I}{Cn}, \quad \text{or} \quad \frac{\Delta V}{V} = \frac{1}{RCn},$$

[32] The type 866 mercury-vapor rectifier is an inexpensive tube which has ample current-carrying capacity and is rated for an inverse peak voltage of 7500. It requires a filament supply of 2.5 volts and 5 amperes.

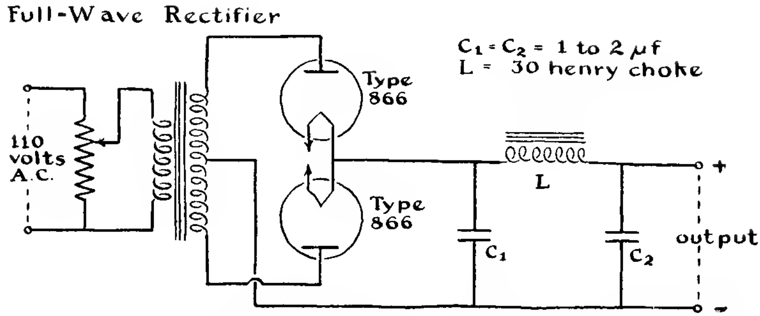


Fig. 24. If power is to be supplied, it is best to use full-wave rectification with a suitable filter.

where ΔV is the fluctuation in the voltage output, R the resistance across the output, and n the number of pulses supplied to the condenser, C, per second.

In case it is desired to draw much current from the output, it is best to rectify both halves of the alternating-current wave. Two 866 tubes may be used as shown in Fig. 24. In this case a transformer with a center-tapped secondary winding and one insulated filament transformer are necessary. The filter consists of two condensers of capacity of 1 to 2 microfarads and a 30-henry choke. The output of such a rectifier and filter unit will have less than a 1 per cent ripple for 60-cycle current when the current drain does not exceed 10 milliamperes.

If a rectified voltage is wanted which is greater than the peak potential supplied by the transformer, a voltage-doubling circuit such as shown in Fig. 25 may be used. The

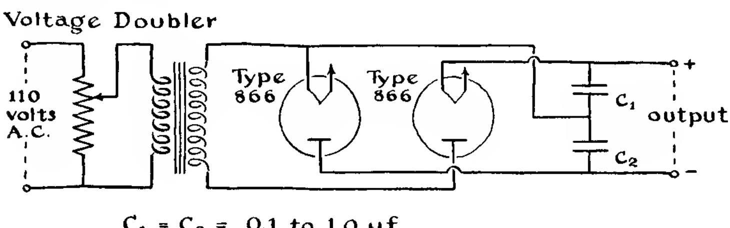


Fig. 25. The above arrangement will double the peak voltage supplied by the transformer. Two separate filament supplies must be used.

voltage output will be double the peak voltage available from the transformer. The circuit shown employs two type 866 mercury-vapor tubes.

If it is desired to regulate the output voltage, a voltage regulator such as will be described later can be used. These devices will also take out the ripple, provided the minimum at any time does not fall below the stabilized voltage.

Voltage regulators. Frequently it is desirable to maintain a constant voltage, for example, when working with a proportional Geiger counter. Several schemes[33] have been devised for accomplishing this, but one of the simplest is that shown in Fig. 26. The action is as follows: As the input potential is raised, no current flows through the 57, owing to the negative bias, until the output potential reaches a point where the grid is at about -3 volts with respect to the cathode. As the input potential is raised still farther, the output potential at first goes up slightly, and then, because of the drop in potential across R_4, reaches a maximum and finally falls. If g_m is the mutual conductance of the tube, the change of output voltage V_o with input V_i can be expressed as

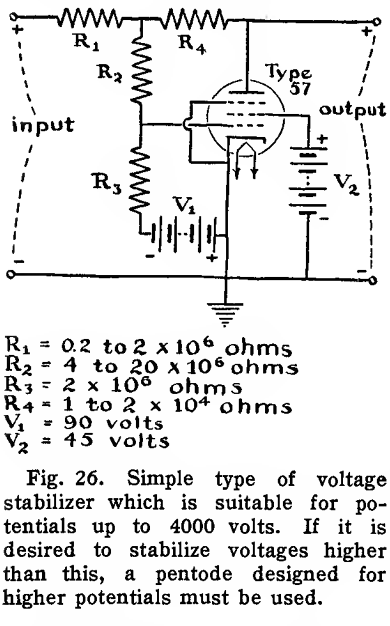


Fig. 26. Simple type of voltage stabilizer which is suitable for potentials up to 4000 volts. If it is desired to stabilize voltages higher than this, a pentode designed for higher potentials must be used.

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[33] See the following:
Ashworth, J. A., and Muzon, J. C., *Rev. Sci. Instruments*, *8*, 127 (1937).
Evans, R. D., *Rev. Sci. Instruments*, *5*, 371 (1934).
Gingrich, N. S., *Rev. Sci. Instruments*, *7*, 207 (1936).
Richards, L. A., *Rev. Sci. Instruments*, *4*, 479 (1933).
Street, J. E., and Johnson, T. H., *Frank. Inst., J.*, *214*, 155 (1932).
Webster, H. C., *Cambridge Phil. Soc., Proc.*, *28*, 121 (1931–1932).

$$\frac{\partial V_o}{\partial V_i} = \frac{R_2 + R_3 - R_3R_4g_m}{R_1 + R_2 + R_3 + R_1R_3g_m}.$$

If $R_4 = 0$, $R_1 = 2 \times 10^6$ ohms, $R_2 = 20 \times 10^6$ ohms, $R_3 = 2 \times 10^6$ ohms, $V_1 = 90$ volts, and $V_2 = 45$ volts, the regulation is about 1 per cent; that is, the change of output voltage is only 0.01 of the change of the input voltage. With $R_4 = 15{,}000$ ohms, and the other quantities the same as before, the maximum occurs experimentally at about 2000 volts input and 1000 volts output, and there is less than 1 volt change in the output when the input voltage is changed

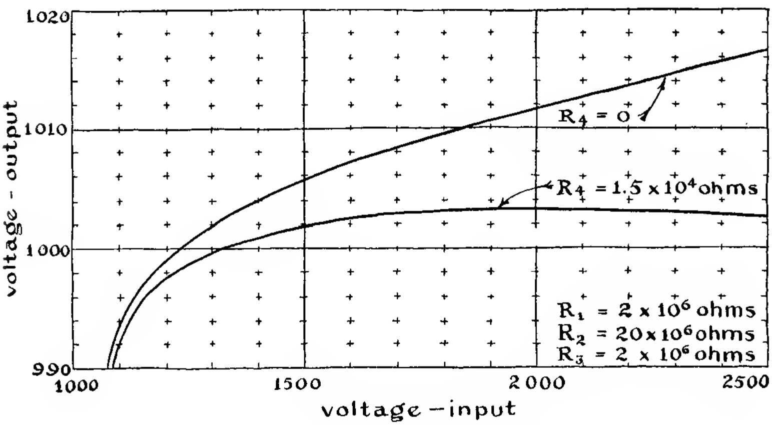

Fig. 27. Typical performance curve for the circuit shown in Fig. 26. With $R_4 = 0$, the regulation is about 1 per cent.

from 1500 to 2500 volts. Experimental results using the above circuit constants are shown in Fig. 27. As R_4 is increased, the maximum becomes sharper and moves down to lower voltages.

If it is desired to draw current from the output and still maintain a constant voltage supply, the above circuit is not satisfactory when more than a fraction of a milliampere of current is used. It is possible, by using the constant current characteristic of another pentode in conjunction with the above circuit, to keep a constant voltage output when the current is changed from 0 to 1 milliampere.

The circuit is shown in Fig. 28. The action may be described as follows: As the input voltage is raised, a point is reached where T_1 becomes conducting, depending upon the ratio of R_2 to R_3. Until this time, T_2 has been in a highly conducting state, with a direct-current resistance probably less than 1000 ohms, because of the +45 volts on the grid. As soon as T_1 becomes conducting, the drop in potential across R_4 becomes approximately V_3+3 volts and tends to remain at this constant value. As the input voltage is still further raised, T_2 continues to carry current but acts as a constant current device, and the voltage is stabilized by the action of T_1, as in the previous circuit. If now current is drawn from the output, the immediate tendency is for the grid of T_1 to go more negative with respect to the cathode. This makes T_1 less conducting, resulting in a less negative potential on the grid of T_2. Thus T_2 becomes more conducting to supply the current delivered to the output.

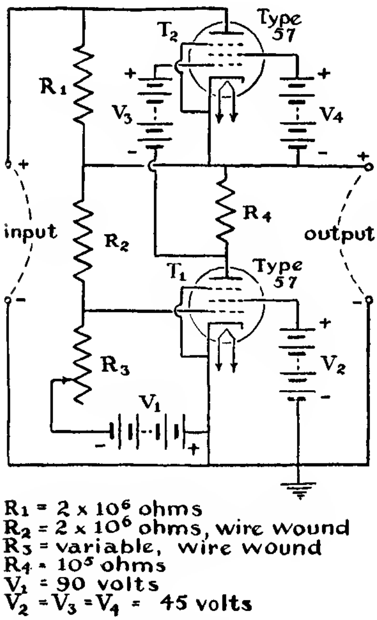

Fig. 28. The above combination of two type 57 tubes permits excellent voltage stabilization for current drains up to 1 milliampere. Drifts may be as low as 0.1 volt per hour in the output. Potentials from several hundred to several thousand volts can be stabilized with this circuit using the type 57 tubes.

The performance of the circuit is illustrated in Fig. 29, where the circuit constants were those in Fig. 28 and $R_3 = 2 \times 10^5$ ohms. The mutual interaction of the two tubes makes for a much more constant voltage regulation at all times than could be had with one tube. Experimentally there was less than 0.1 volt change in the output of 1039.5

volts when the input changed from 1050 to 2500 volts. A change from 0 to 1 milliampere drain at any input voltage above the stabilized value changes the output voltage by less than 0.2 volt. When more current than this is drawn, the constant voltage characteristic of the circuit gradually disappears.

None of the resistances or potentials in the circuit are critical except V_1 and the ratio of R_2 to R_3. For constancy, R_2 and R_3 should be wire wound and kept at the same temperature. If V_1 is supplied by new "B" batteries of the dry-cell type, very satisfactory results will be obtained,

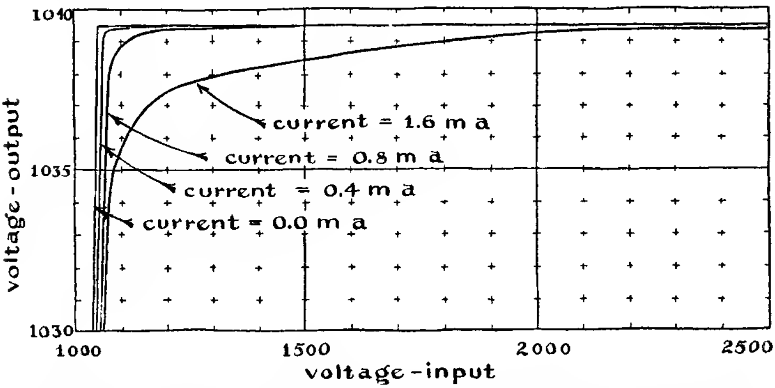

Fig. 29. Typical performance curves for the circuit shown in Fig. 28. At no current drain there is less than 0.1 volt change in the output of 1039.5 volts when the input changes from 1050 to 2500 volts.

since their temperature coefficient is exceedingly small. The heater supply of T_2 is not at all critical, and a change of 50 per cent in the power input changes the output voltage of the circuit less than 0.1 volt. However, a change of 50 per cent in the power input to the heater of T_1 changes the output voltage by about 5 volts in 1000. Extended tests showed that after the first half hour, drifts may amount in the extreme cases to 1 volt per hour but may be as small as 0.1 volt per hour.

It will be noted that the output voltage is within a few volts of the input voltage until the constant voltage region

begins, and that thereafter the power dissipation is in a radio tube and not in resistances. By changing R_3 (Fig. 28) it is possible to achieve equal performance of the circuit from several hundred to several thousand volts.

This type of constant voltage device is a valuable aid in eliminating the ripple from rectified alternating current. A condenser of low capacity can be used in the filter, and these circuits will take out the remainder of the ripple, provided the lowest potential reached is not below the stabilized voltage.

Although the type 57 and similar tubes are rated by the manufacturer at about 250 volts on the plate, much higher voltages than this may be applied if the wattage dissipation is kept low. The limiting factor is usually sparking over in the base of the tube. Almost all of the tubes of this type will stand 2000 volts on the plate, and many of them will not break down under 4000 to 5000 volts.

Discussion of probabilities and errors in Geiger counter work. *Time between individual particles.* If the particles are all independent of one another, they arrive at random, and the laws of probability can be applied. Assuming a constant source of radiation, the probability of finding a time interval between t and $t + dt$ is given by[34]

$$P_t dt = \frac{1}{\bar{t}} e^{-\frac{t}{\bar{t}}} dt, \tag{1}$$

where $\bar{t}$ is the average value of the time interval. Then the probability of finding a time interval between t_1 and t_2 is given by

$$\int_{t_1}^{t_2} P_t dt = e^{-\frac{t_2}{\bar{t}}} - e^{-\frac{t_1}{\bar{t}}}. \tag{2}$$

In particular, if we want to know the probability of finding a time interval equal to or less than the average time interval $\bar{t}$, we get $(1 - 1/e) = 0.632$, and the probability of finding a time interval between $\bar{t}$ and infinity is 0.368. In

[34] See: *Handbuch der Exp. Physik,* XV, 786 (1928). Wein, W., and Harms, F., editors, Leipzig (1928).

the case of a mechanical recorder which will not respond to pulses separated by a time less than τ, it is possible to find the average number of counts missed as follows: Let the average time between pulses, $\bar{t}$, be large compared with τ. Then Eq. 2 gives the probability of finding a time interval less than τ. To the first order of approximation this probability is $\tau/\bar{t}$. Thus, if N is the total number of particles counted, the mean error in the count will be $N\tau/\bar{t}$, and the mean relative error will be $\tau/\bar{t}$.

Number of particles in a given time. If the number of particles from a constant source of radiation is counted for a certain length of time and compared with the number counted again for the same length of time, the two values will, in general, be different. The relative error of a single set of counts will, of course, decrease as the number of counts is increased.

If $\bar{n}$ is the average number of particles arriving in a certain time, as determined by a long period of counting, and n is the actual number arriving in this time, the probability of finding this number n is given by Poisson's law[35]

$$P_n = \frac{(\bar{n})^n e^{-\bar{n}}}{n!}. \tag{3}$$

Thus, if by counting a large number of particles, it is found that on the average there are 100 per minute from a certain source, then the probability that in this same time 100 will actually be counted is 0.04, and the probability of 50 being counted is only about 10^{-8}. There is a certain probability of any number being counted, but obviously

$$\sum_0^\infty P_n = 1.$$

Error in a single count of n particles. If the mean or root mean square error, ϵ_m, is defined by

$$\epsilon_m^2 = \sum_0^\infty (n - \bar{n})^2 P_n,$$

[35] Bateman, H., *Phil. Mag.*, *20*, 704 (1910).

then application to Poisson's law gives

$$\epsilon_m = (\bar{n})^{1/2}, \tag{4}$$

and the probable error[36] is $0.67\epsilon_m = 0.67\, n^{1/2}$, since for large values, n differs from $\bar{n}$ by only a small amount. The mean relative error, therefore, is ϵ_m/n, or $n^{-1/2}$. In order to have a probable error of 1 per cent in a single set of counts, it is, therefore, necessary to count 4300 particles; and to have a probable error of 0.1 per cent, 4.5×10^5 particles must be counted.

Error introduced by background. If a single counter is used to measure the activity of a source of radiation which is comparable with the natural count of the counter due to background, it is important to know the effect of the background upon the accuracy of the measurements.

If the error of one set of counts is ϵ_1, and the error in another set of counts is ϵ_2, then the error of the sum or difference will be

$$\epsilon = (\epsilon_1{}^2 + \epsilon_2{}^2)^{1/2}. \tag{5}$$

Consequently, if there are N_1 counts due to a certain radiation plus the background and N_2 counts due to the background only, the mean error of the difference, which is the effect of the source being measured, is $(N_1 + N_2)^{1/2}$, so that the relative mean error is $(N_1 + N_2)^{1/2}/(N_1 - N_2)$, and the relative probable error becomes[37]

$$\frac{\epsilon_p}{N_1 - N_2} = 0.67\frac{(N_1 + N_2)^{1/2}}{(N_1 - N_2)}. \tag{6}$$

As an example, if the counting when the source to be measured is present is twice what it is when only the background is being measured, then it is necessary to count $6 \times 4500 = 27{,}000$ counts with the source present to reduce the probable error of the difference to 1 per cent. This is six times as many counts as would be needed if no background were present. The counting time will be three times as long.

[36] See any book on errors for the relation between mean and probable errors.

[37] See also Evans, R. D., and Mugele, R. A., *Rev. Sci. Instruments*, 7, 441 (1936).

In addition, half of this number must be counted when only the background is present, so that altogether $9 \times 4500 = 40{,}500$ counts must be made, which will take six times as long as if there were no background.

Errors due to accidentals in counting coincidences. If two counters are used to count coincidences between them, it will be found that even when the counters are separated by great distances in a horizontal direction, so that cosmic rays do not contribute to the coincidences, there remains a background of counts. These "accidentals" must usually be taken into account, especially when the real coincidences become of the same order of magnitude.

In a coincidence circuit using two tubes, if a pulse arrives at one amplifying tube within a certain time τ either before or after a similar pulse arrives at the other tube, where τ is the resolving time, a coincidence will be recorded. There is a certain probability that two unrelated pulses will thus be recorded as a coincidence, which, of course, is spurious.

Let the time widths of the pulses from each counter be equal. Then the resolving time will be defined as that time width of a pulse which will just respond as a coincidence when the peak of another similar pulse falls without a time 2τ of the first.

Let there be an average of N_1 pulses per second from one counter and an average of 1 per second from another counter. Then the probability that one will fall within a time width of one of the N_1 pulses will be $2\tau N_1$; and if there are 2 per second on the average from the one counter, then the number of accidentals will be $2(2\tau N_1)$, and so forth; and for N_2 per second the number of accidentals will be on the average

$$A_{12} = 2\tau N_1 N_2. \tag{7}$$

For the case of three counters connected to count triple coincidences, it is easily shown that the number of accidentals per second is given by

$$A_{123} = 3\tau^2 N_1 N_2 N_3, \tag{8}$$

when the counters are all separated in such a way that there

are no real coincidences between any of the counters. The generalization of Eq. 8 for any number of counters n connected to count coincidences is

$$A_{12\,.\,.\,.\,n} = n\tau^{n-1}N^n, \tag{9}$$

where it is assumed that N and τ are the same for all counters. This last equation provides a ready means of determining the resolving time of the counter circuit. It is necessary only to separate the counters in a horizontal plane to such distances that the number of real coincidences between any two due to cosmic rays coming in near the horizon is small compared with the true accidentals, and to record the accidentals as well as the counting rate of one of the n similar counters.

In case the τ's and N's are all different, then, as Eckart and Shonka[38] have shown, the generalized expression becomes:

$$A_{12\,.\,.\,.\,n} = N_1N_2\,.\,.\,.\,N_n\tau_1\tau_2\,.\,.\,.\,\tau_n\left(\frac{1}{\tau_1} + \frac{1}{\tau_2} + \,.\,.\,.\,\frac{1}{\tau_n}\right).$$

Consistency of data. To check whether or not a counter set is operating properly, it is usually desirable to compute the probable error of the final result in two different ways. If these agree in general to within the required limits, then it may be assumed that the counters have been working consistently and that instrumental fluctuations have been negligible.

Let the mean error in a single determination of N_1 counts be ϵ_1, the mean error in another determination of N_2 counts be ϵ_2, and so forth. Then by an extension of Eq. 5 the mean error of the result of n determinations is

$$\epsilon_m = (\epsilon_1^2 + \epsilon_2^2 + \,.\,.\,.\,\epsilon_n^2)^{1/2},$$

or, by Eq. 4,

$$\epsilon_m = (N_1 + N_2 + \,.\,.\,.\,N_n)^{1/2},$$

and the probable error is

$$\epsilon_p = 0.67(N_1 + N_2 + \,.\,.\,.\,N_n)^{1/2}.$$

[38] Eckart, Carl, and Shonka, Francis R., *Phys. Rev.*, *53*, 752 (1938).

On the other hand, if N_1, N_2, and so forth, are taken over equal periods of time, the average value for this period of time will be

$$N_{\text{av.}} = \frac{N_1 + N_2 + \ldots N_n}{n}.$$

Let the residuals $(N - N_1)$, $(N - N_2)$, $\ldots (N - N_n)$ be denoted by r. Then the probable error of the result will be

$$\epsilon_p' = 0.67\left(\frac{\Sigma r^2}{n(n-1)}\right)^{1/2}.$$

If there are instrumental fluctuations entering, then ϵ_p' is usually greater than ϵ_p. If ϵ_p' is approximately equal to ϵ_p, it can be safely assumed that the counters are working consistently, for there is an even chance that the actual error will be greater than that computed, 1 chance in 4.6 that it will be greater than twice that computed, and only 1 chance in 22 that it will be greater than three times that computed.

TABLE I

TEST ON THE CONSISTENT BEHAVIOR OF TWO G-M COUNTERS COUNTING COINCIDENCES. N IS THE NUMBER OF COUNTS PER HOUR TAKEN WITH AN AUTOMATIC CAMERA, AND r THE DEVIATION FROM THE MEAN OR THE RESIDUAL

N	r	r^2	N	r	r^2
3349	+ 5	25	3392	+ 38	1444
3333	− 21	441	3318	− 36	1296
3429	+ 75	5625	3232	− 122	14,884
3278	− 76	5776	3383	+ 29	841
3404	+ 50	2500	3292	− 62	3844
3308	− 46	2116	3500	+ 146	21,316
3292	− 62	3844	3340	− 14	196
3339	− 15	225	3481	+ 127	16,129
3373	+ 19	361	3295	− 59	3481
3350	− 4	16	3395	+ 41	1681

$\Sigma N = 67{,}083 \quad \Sigma r^2 = 86{,}021$

$N_{\text{av.}} = 3354.1$

Numerical example. The data shown in Table I were found with two large G-M counters counting coincidences,

by taking readings every hour with an automatic camera. The probable error computed from the residuals is therefore

$$\epsilon_p' = 0.67\left(\frac{\Sigma r^2}{n(n-1)}\right)^{1/2} = 10.1,$$

and the number of counts per hour with the probable error is

$$3354.1 \pm 10.1.$$

Computed from the number of counts, the probable error in 67,083 is $0.67(67{,}083)^{1/2} = 174$, and the number of counts per hour with the probable error can be written

$$3354.1 \pm 8.7.$$

It will be noticed that the probable errors computed in these two ways are nearly equal, although that computed from the residuals of each hourly reading is somewhat larger. However, there is no systematic trend in the data, there being nearly equal positive and negative residuals. An application of Chauvenet's[39] criterion to these data shows that a single residual must be larger than 150 in order to be rejected. No residual in the example should, therefore, be discarded. Consequently it may be concluded that there are no appreciable instrumental fluctuations entering into the result.

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[39] Palmer, Albert de Forest, *Theory of Measurements*, page 127. New York: McGraw-Hill Book Company, 1912.

CHAPTER VIII

Vacuum Thermopiles and the Measurement of Radiant Energy

BY

C. HAWLEY CARTWRIGHT AND JOHN STRONG

A RADIOMETRIC instrument consists of a blackened receiver, which is heated by the radiant energy to be measured. The instrument is provided with some physical means for measuring the rise in temperature of the receiver produced by the radiant energy. For the most delicate measurements the means employed must be responsive to a rise of temperature of the order of a few millionths of a degree.

In comparison with other methods of measuring light intensity, a radiometric instrument is characterized by the direct and simple way in which the response depends on the intensity of the light; the relation between these two quantities is linear. Also, the instrument is generally characterized by equal sensitivity for all wave lengths.

For measuring the intensity of radiant energy at wave lengths less than 1μ, radiometric instruments are more reliable but less sensitive than other instruments such as photoelectric or photographic photometers. Accordingly, a radiometric instrument is frequently used as a reference instrument for the calibration of photoelectric and photographic photometers. In infrared spectroscopy, however, the radiometric instrument is the most sensitive instrument now available.

When a radiometric instrument is giving its full response to a beam of light incident on the receiver, the rate at which

the heat is lost by the receiver is in equilibrium with the rate at which heat is absorbed from the light beam, Φ_a. Inasmuch as the heat lost by the receiver is proportional to the produced rise in temperature, ΔT, we can write

$$\Phi_a = L_1\Delta T + L_2\Delta T + L_3\Delta T + L_4\Delta T, \qquad (1)$$

where the L's represent the heat losses in unit time per unit temperature change. Thus, L_1 represents the loss of heat by radiation from the receiver, L_2 the loss by air conduction, L_3 the loss by conduction through members touching the receiver, and L_4 any other means of losing heat, such as, in the case of a thermopile, Peltier heat loss. Obviously, it is desirable to have the L's small, and for this reason the energy is to be concentrated onto a small receiver to reduce L_1. Furthermore, the receiver is usually mounted in a high vacuum in order to make L_2 vanish.

The response of the instrument is determined by the magnitude of ΔT, and different radiometric instruments are characterized by the manner in which ΔT is measured.

A thermopile measures ΔT by means of one or more thermoelectric junctions attached to the receiver.[1]

A microradiometer measures ΔT in the same manner as a thermopile.[2] In this instrument, however, the thermo-

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[1] Brackett, F. S., and McAlister, E. D., *Rev. Sci. Instruments*, *1*, 191 (1930).
Burger, H. C., and van Cittert, P. H., *Zeits. f. Physik*, *66*, 210 (1930).
Coblentz, W. W., *Bureau of Standards, Bull.*, *11*, 131 (1914).
Firestone, F. A., *Rev. Sci. Instruments*, *1*, 630 (1930).
Johansen, E. S., *Ann. d. Physik*, *33*, 517 (1910); *Phys. Zeits.*, *14*, 998 (1913).
Lebedew, P., *Ann. d. Physik*, *9*, 209 (1902).
Moll, W. J. H., *Inaug. Dissertation Utrecht* (1907); *Arch. Neerland*, *13*, 100 (1908).
Moll, W. J. H., and Burger, H. C., *Zeits. f. Physik*, *32*, 575 (1925); *Phil. Mag.*, *50*, 618 to 631 (1925).
Paschen, F., *Ann. d. Physik*, *33*, 736 (1910).
Pettit, Edison, and Nicholson, Seth B., *Astrophys. J.*, *56*, 327 (1922).
Pfund, A. H., *Phys. Zeits.*, *13*, 870 (1912).
Rubens, H., *Zeits. f. Instrumentenk.*, *18*, 65 (1898).

[2] Boys, C. V., *Roy. Soc., Proc.*, *42*, 189 (1887), *44*, 96 (1888), *47*, 480 (1890); *Roy. Soc., Phil. Trans.*, *180A*, 169 (1889).
Coblentz, W. W., *Bureau of Standards, Bull.*, *2*, 479 (1906).
Paschen, F., *Ann. d. Physik*, *48*, 272 (1893).

junctions and receiver are attached to the moving system of a galvanometer coil, which is suspended on a fine quartz fiber. The superiority of the microradiometer over a thermopile lies in the fact that, because no outside lead wires are required, energy losses in electrical resistance are diminished. However, the combination of the thermopile and galvanometer makes an instrument which is awkward to use in a spectrometer, because it must be protected from vibration in its operating position.

A bolometer consists of a blackened thin metal strip with electrical connections.[3] This strip forms the receiver for the radiations. It is connected as one arm of a balanced Wheatstone bridge. The change in the electrical resistance of the strip, as measured by a sensitive bridge galvanometer, is a measure of ΔT.

A radiometer consists of a system composed of a receiver and a mirror which is mounted in a partially evacuated case. The system is suspended by a fine quartz fiber. The back of the receiver is thermally insulated from the front, so that when a beam of light falls on the receiver, the front is heated more than the back.[4]

The radiometer is most sensitive at a gas pressure of about 0.06 mm of mercury. The gas molecules which strike the side of the receiver which is warmed by the radiations leave it with a greater velocity than those which strike the opposite and cooler side, and therefore a net backward recoil is exerted. This results in a deflection of the system until the recoil torque is balanced by the torque arising from

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[3] Langley, S. P., *Am. Acad., Proc.*, *16*, 342 (1881); *Annals of the Astrophysical Obs.*, *4*, 45 (1904), *5*, 75 (1905).
Leimbach, G., *Ann. d. Physik*, *33*, 308 (1910).

[4] Abbott, C. G., *Astrophys. J.*, *69*, 293 (1929).
Coblentz, W. W., *Bureau of Standards, Bull.*, *4*, 391 (1908), *9*, 15 (1913).
Crookes, Sir William, *Roy. Soc., Phil. Trans.*, *11*, 166, 325 (1876).
Sandvik, O., *J.O.S.A.*, *12*, 355 (1926).
Hettner, G., *Zeits. f. Physik*, *27*, 12 (1924).
Nichols, E. F., *Phys. Rev.*, *4*, 297 (1897).
Smith, S., *Nat. Acad. Sci., Proc.*, *16*, 373 (1930).
Tear, J. D., *Phys. Rev.*, *23*, 641 (1924).

torsion of the quartz fiber. The deflection of the system, as indicated by the mirror, is a measure of the temperature difference, ΔT, between the front and back surfaces of the receiver.

Anyone interested in radiometers will find some of the important papers on this subject listed in the footnotes. One of the features of the radiometer is its constant sensitivity. This reproducibility of the deflection is due partly to the use of a quartz suspension but mostly to the fact that the required pressure (0.06 mm of mercury) is one that is easily maintained permanently in a closed-off system. The radiometer has been used successfully in the microphotometer. The application of the radiometer to the microphotometer places but little demand on flexibility.

When maximum sensitivity is desired for very delicate measurements, the problem arises of choosing which type of radiometric instrument will be most sensitive, and further, which design of a given type will be most sensitive.

There are conflicting reports on the ultimate sensitivities obtainable with the different types of radiometric instruments. The thermopile is certainly almost as sensitive as any other radiometric instrument, and although other instruments might be made slightly more sensitive than vacuum thermopiles, they are usually more difficult to construct and use.[5] Accordingly, in our treatment here, the construction details of radiometric instruments other than the thermopile will be omitted. Vacuum thermopiles are widely used by experimenters in infrared spectroscopy, possibly more often than all other types of radiometric instruments taken together.

Construction and evacuation of a sensitive thermopile. The construction of a vacuum thermopile of the type shown in Fig. 1 will be described here.[6] This thermopile has two

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[5] Cartwright, C. H., *Physics*, *1*, 211 (1931).
Klumb, Hans, *Zeits. f. techn. Physik*, *17*, 279 (1936).

[6] We wish to acknowledge the contributions to this design of Professor Firestone and Mr. Paul Weyrich, of the University of Michigan.

independent junctions and receivers. Four external leads are provided, so that these junctions either can be used separately or can be connected together in series or in oppo-

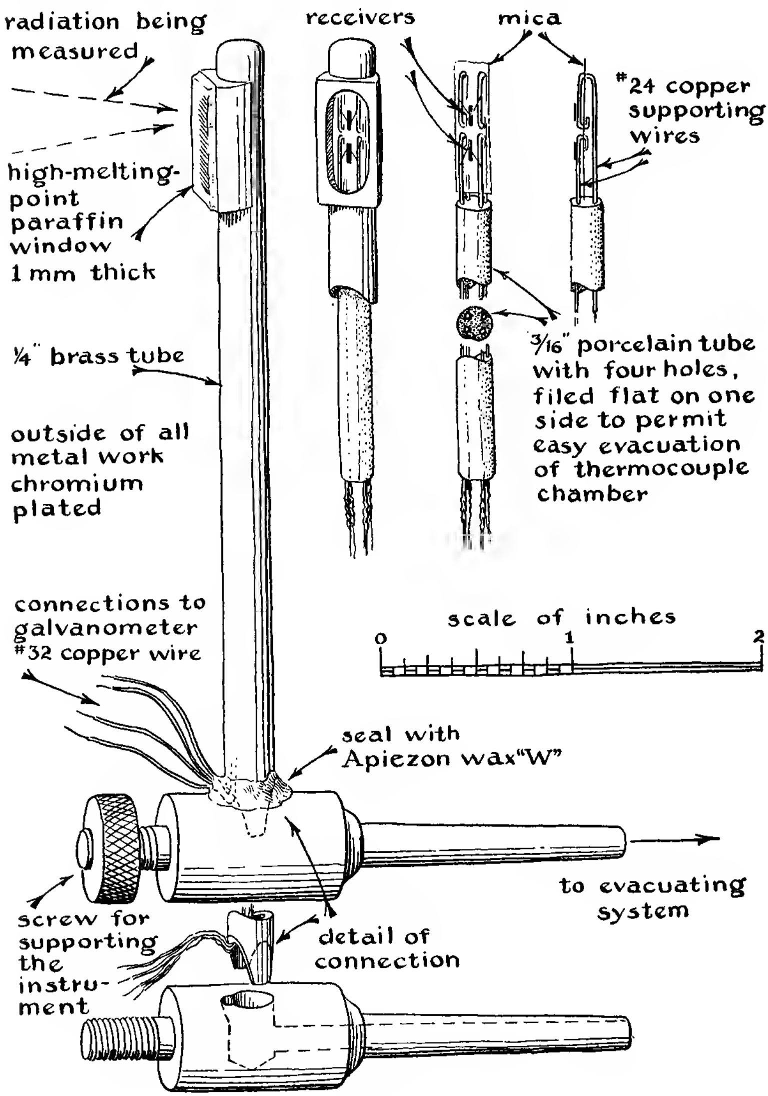


Fig. 1.

sition. The thermopile is made compensating by connecting the junctions in opposition. The receivers are rectangular and are placed end to end—an arrangement especially suited to spectroscopic investigations. For special problems the shape of the receivers as well as other features of the design can, of course, be altered.

A crystalline quartz window is attached with Apiezon wax "W." This wax is also used to seal the other joints. Apiezon wax "W" is easy to apply and has an extremely low vapor pressure—a valuable feature for maintaining a permanent high vacuum.

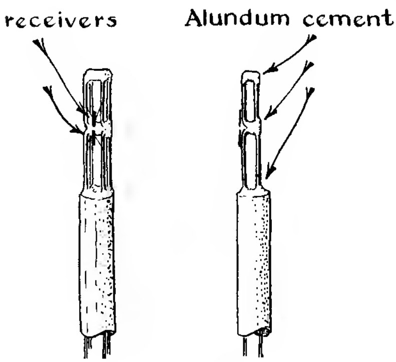


Fig. 2.

A porcelain rod of $\frac{3}{16}$ inch in diameter containing four holes holds the relatively heavy copper wires on which the thermojunctions are mounted. The projecting copper wires are fastened together by mica as shown in Fig. 1 or by Alundum cement as shown in Fig. 2 so that they will not vibrate. Four flexible and insulated copper leads are soldered to these heavier copper wires, as shown in Fig. 1, and these are brought outside the housing through one of the wax seals.

Fig. 3 shows one method for maintaining a high vacuum of better than 10^{-4} mm of mercury in a thermopile. The Pyrex tube shown here is filled with activated charcoal. The charcoal tube is evacuated and baked for several hours to outgas it before the stopcock is closed to isolate the system from the pumps. At first the vacuum will be maintained at better than 10^{-4} mm of mercury for only a few hours. However, each time the thermopile is re-evacuated the vacuum lasts longer, so that after about five evacuations, if the system is tight, the vacuum will remain good for a month or so. The vacuum is tested by measuring the sensi-

tivity of the thermopile under some convenient standard condition, such as that of exposing the thermopile to a 60-watt lamp placed 10 inches away and measuring the response of the junction with a relatively insensitive galvanometer. The degree of vacuum obtaining in a thermopile should not be tested with a spark, since electrostatic forces may destroy the junctions.

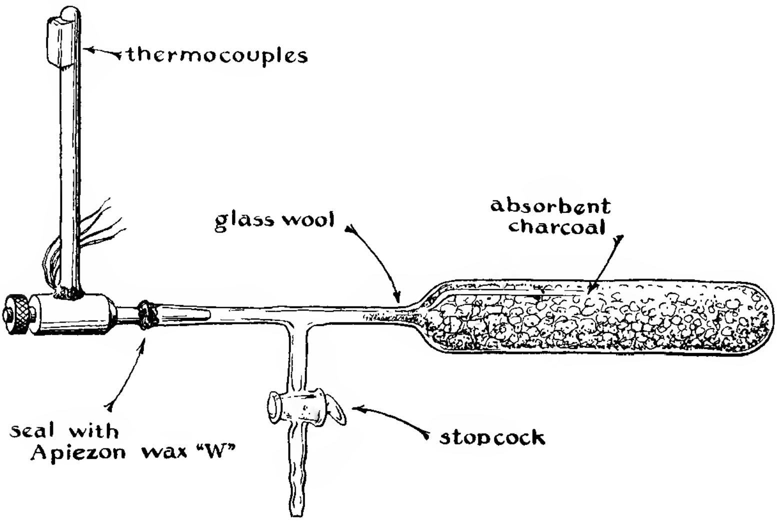


Fig. 3. (Use Apiezon wax "W" on the stopcock.)

Wires for the thermojunctions. One thermoelectric wire is made of pure bismuth, and the other is an alloy of bismuth and 5 per cent tin. The selection of this combination of wires to form thermojunctions has been made after a consideration of the Wiedemann-Franz coefficients, as well as of the thermoelectric powers of various possible combinations, including such metals as tellurium and the other bismuth alloys.[7]

The resistance of each thermoelectric wire should be at least 10 ohms, and the wire should not be longer than 3 mm. A bismuth wire 3 mm long with a resistance of 10 ohms has

[7] Cartwright, C. H., *Zeits. f. Physik*, *92*, 153 (1934); *Ann. d. Physik*, *18*, 656 (1933).

a diameter of about 24μ. The bismuth-tin alloy wire should have about 20 per cent more electrical resistance than the pure bismuth wire, because of the influence of the Wiedemann-Franz coefficient. However, owing to the greater specific electrical resistance of the bismuth alloy wire, its diameter will be about 7μ greater than the diameter of the pure bismuth wire.

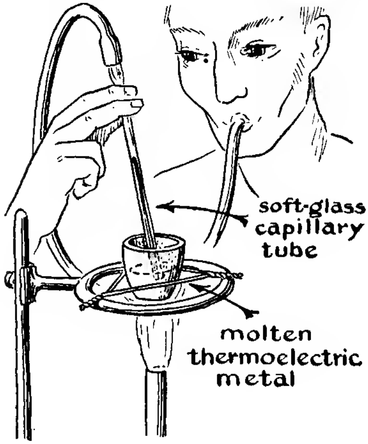


Fig. 4.

Preparation of the alloy wires. Thermoelectric wires can be purchased from the Baker Company, Newark, New Jersey, or they may be prepared by the Taylor process. To make the wires by the Taylor process, the thermoelectric metal is melted and sucked up into a thin-wall capillary tube of soft glass. (See Fig. 4.) This tube, containing the metal as a core, is heated in a small electric furnace and drawn out in the manner shown in Fig. 5. The

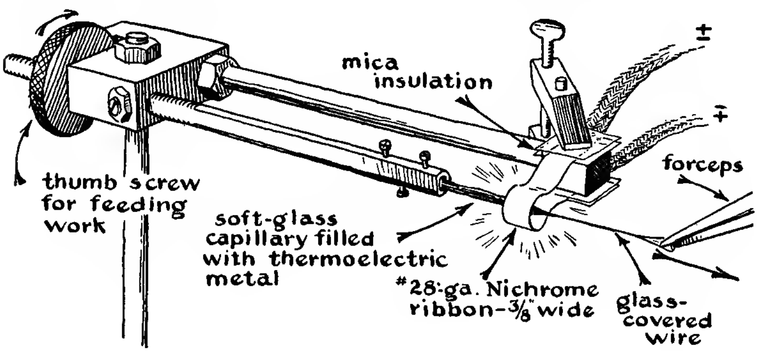


Fig. 5.

diameter of the wires produced in the composite drawn fibers is controlled by the temperature of the furnace and the speed of drawing. When the temperature of the furnace is

properly regulated, the wires obtained are single crystals which can be bent and straightened repeatedly without breaking. Wires which are brittle should be discarded.

The glass is removed from the composite fibers with hydrofluoric acid, which dissolves the soft glass readily but scarcely corrodes or etches the metal. The hydrofluoric acid, usually diluted with a little water to suppress fuming, is conveniently held either in a shallow dish which has been coated with paraffin or simply in a groove melted in a block of paraffin. The wires are withdrawn from the acid with metal forceps and washed in a weak solution of Aerosol.[8] (Avoid letting the acid come in contact with the fingers.) The wires must be freed from all glass or difficulty in cutting and soldering will be encountered. About 5 minutes in the acid is required.

The good wires are mounted in flat cigar boxes, one for each of the metals. The electrical resistance of each wire should be measured and its resistance per unit length noted on a small label attached opposite the wire. After an assortment of wire sizes has been collected and measured, one is prepared to proceed with the construction of junctions of prescribed characteristics.

Construction of the junctions. A microscope of about 10-power magnification facilitates the manipulation and soldering of the thermoelectric wires. An erecting binocular type giving stereoscopic vision is ideal.

Fig. 6 illustrates the manner of soldering the thermoelectric wires to the copper supporting wires with a hot tinned sewing needle. The hot-wire device used for heating the needle is electrically heated, the heat being regulated by a resistance. The temperature of the tip of the sewing needle

[8] Aerosol or the detergent Dreft, the latter of which is sold in grocery stores, has many uses around the laboratory. Besides its usefulness in washing glass, aluminum mirrors, and so forth, it can be added to water to decrease its surface tension and increase wetting power. This is advisable for washing thermocouple wires, as the solution wets the wires and dissolves the hydrofluoric acid. Also, for coating the receivers, the solution with added Dreft has less "attraction" due to surface tension, and accordingly there is less danger of destroying the work when the brush with its blackening material is applied.

can be further controlled by varying the point of contact between the hot wire and the tip of the needle.

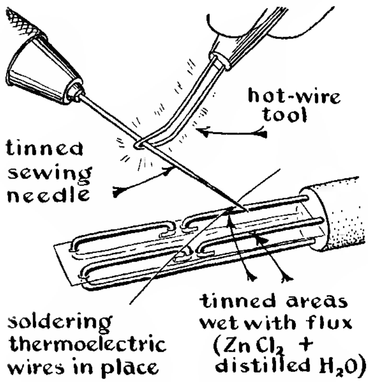
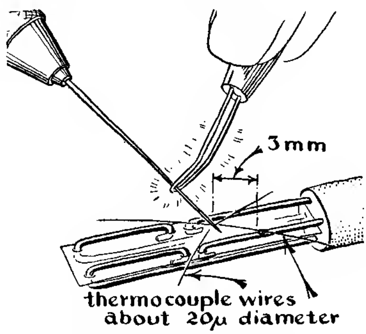


Fig. 6.

Wood's metal is used for soldering. A solution of pure zinc chloride in distilled water is used as flux. After the soldering is completed, the excess zinc chloride should be carefully removed with a small brush wet with distilled water.

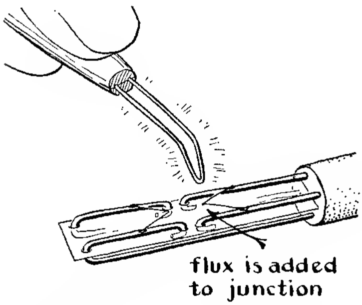
When the thermoelectric wires, which are selected for size so that each will be about 3 mm long, are soldered to the tinned copper supports, they are then "cut" to the proper length by touching them with the hot tinned needle as shown in Fig. 7. This not only "cuts" the wires but tins their ends at the same time. Difficulty with this operation will be encountered unless all of the glass has been dissolved off the wires.



cutting thermoelectric wires
Fig. 7.

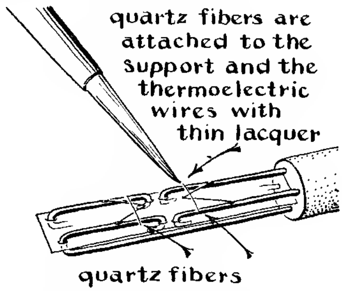
These thermoelectric wires are now manipulated with a cold needle so that their ends are in contact. A little flux is added to their junction, and the soldering is effected by heat radiated from the hot-wire device. (See Fig. 8.) The junction is to be carefully watched. The instant to withdraw the heat is indicated by a slight jerk of the tips of the wires due to surface tension of the fused metal. If the resistance is too great, each wire is shortened by heating the Wood's metal at the base of the wire. Molten Wood's metal pulls in the thermocouple wire by surface tension.

The needle is used to heat the Wood's metal. In this way, it is easy to construct two junctions with only a fraction of an ohm difference in their electrical resistances; and, if the



soldering the junctions

Fig. 8.



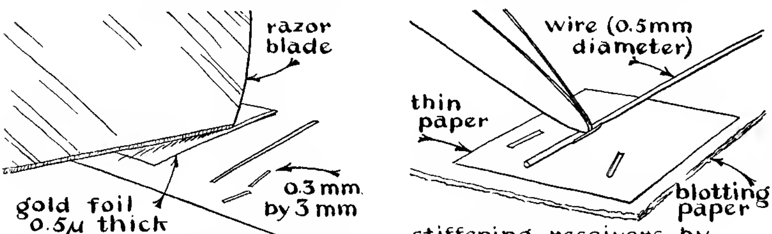
supporting the junctions

Fig. 9.

wires used have been taken from the same stock piece of bismuth or alloy wire, the sensitivities of the junction will match closely.

Ruggedness in the final thermopile is obtained by the use of fine quartz fibers to support the thermoelectric wires and attached receivers. The quartz fibers are fastened to the copper supporting wires by thin lacquer as illustrated in Fig. 9.

The receivers are made of thin gold foil of about 0.5μ thickness. This is considerably thicker than sign painters'



method of cutting receivers

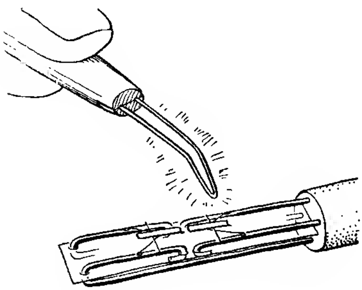
stiffening receivers by curving them

These operations are best performed under a 10-power microscope.

Fig. 10.

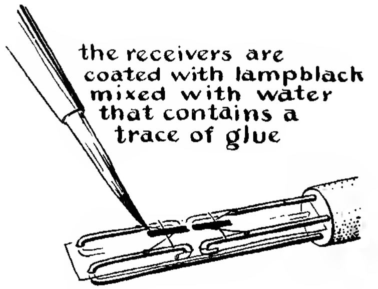
gold leaf.[9] The receivers are cut to size (3 mm by 0.3 mm is a convenient size for spectroscopy) on the stage of the 10X microscope by means of a razor blade as shown in Fig. 10. The receivers are strengthened mechanically by giving them a cylindrical curvature in the following manner: The receiver is placed on a sheet of thin fine-grade paper mounted on blotting paper, and a rod of about 0.5 mm in diameter is pressed against it. (See Fig. 10.) Gold is particularly suitable for receivers because it is easily soldered.

A tiny bit of Wood's metal fused to the junction by radiation and wetted with flux facilitates attaching the receiver.



soldering receivers in place

Fig. 11.



blackening the receivers

Fig. 12.

The gold receiver is laid in contact with the thermojunction and soldered by heating it with radiation from the hot-wire device. (See Fig. 11.) A slight jerk of the receiver indicates when the heater should be withdrawn.

After the receivers are soldered in place, they are blackened with lampblack or other blackening material with the aid of a very small amount of glue as a binder. This mixture is applied to the receiver with a small camel's-hair brush as shown in Fig. 12.

[9] Gold leaf of the required thickness is prepared by evaporating a proper amount of gold in vacuum (see Chapter IV) from a tungsten coil onto a glass plate. The film is then washed off the glass with a stream of water.

Finally, two quartz fibers are fastened over each receiver for added ruggedness. The fibers are so fine and at the same time such poor heat conductors that the ruggedness gained by their use more than compensates for the negligible heat leakage which they introduce. Fig. 13 illustrates the method of securing the receivers and shows the completed thermopile.

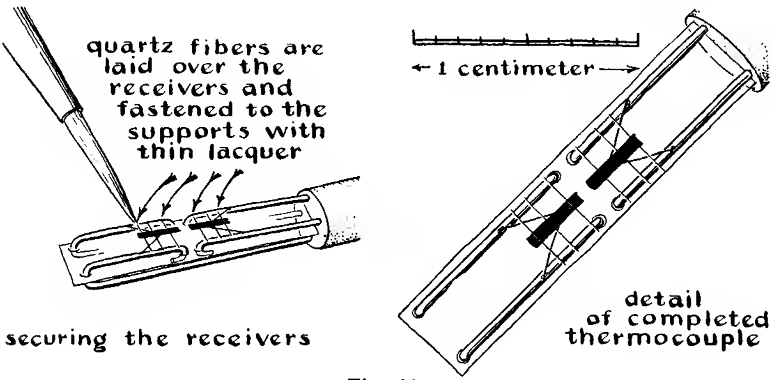


Fig. 13.

Alternative methods of constructing thermopiles. Some experimenters prefer to make the housing for a thermopile from blown glass. Fig. 14 shows a popular type of glass housing. Fig. 15 shows how the junctions are manipulated in the field of the binocular microscope.

TABLE I

MATERIALS FOR THERMOPILE WINDOWS

Window Material	Spectral Region for Investigation
Crystalline quartz	Ultraviolet to 3.5μ
Fluorite	Ultraviolet to 9μ
NaCl	Ultraviolet to 17μ
KCl	Ultraviolet to 21μ
KBr	Ultraviolet to 30μ
KI	Ultraviolet to 35μ
High-melting-point paraffin	20μ to ∞
Crystalline quartz	45μ to ∞

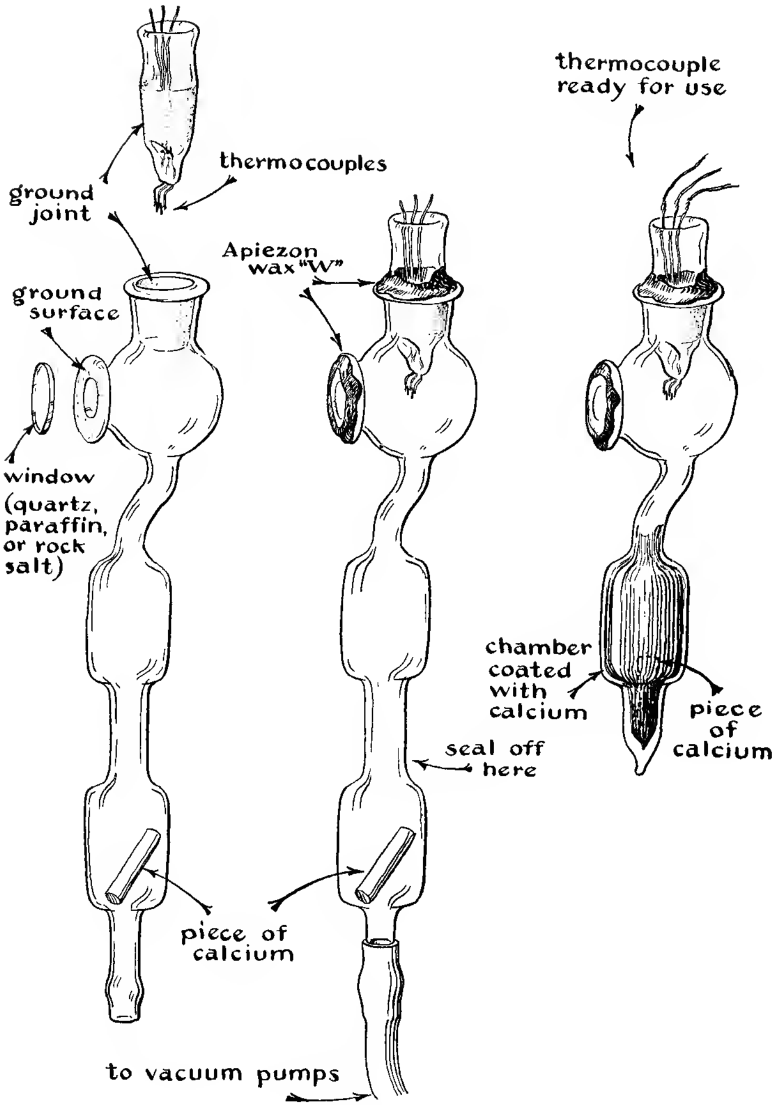

thermocouple ready for use
thermocouples
ground joint
Apiezon wax "W"
ground surface
window (quartz, paraffin, or rock salt)
chamber coated with calcium
piece of calcium
seal off here
piece of calcium
to vacuum pumps

Fig. 14.

The selection of the proper window material for the thermopile is governed by the spectral region in which it is to be used. The appropriate choice can be made from the data given in Table I.

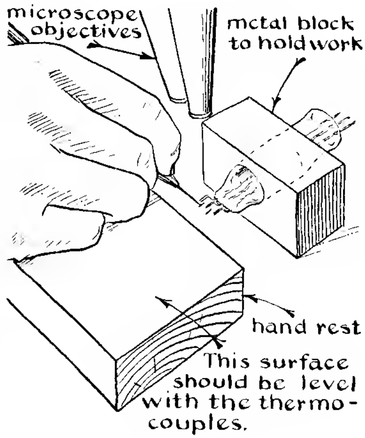


Fig. 15.

High-melting-point paraffin for use in the far infrared, listed in Table I, should not be confused with ordinary low-melting-point paraffin. High-melting-point paraffin is a crystalline material that does not deform when it is subjected to small stresses. In order to obtain strength and at the same time have the paraffin window very thin, it is advisable to make the window cylindrical. Fig. 16 illustrates a method of using a tube of paraffin turned out in the lathe. It is sufficient to have the cylindrical paraffin window only 1 mm thick. Inasmuch as the thermopile cannot be seen through the paraffin window, it is necessary to adjust the receivers to the focal point of the radiations with the help of the galvanometer.

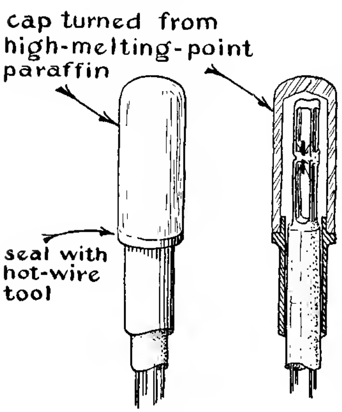


Fig. 16.

Although the Taylor process for preparing thermoelectric wires is recommended, it is possible to obtain wires by the process used by Professor A. H. Pfund, whereby the molten metal is spashed on a plate of glass. One may either select small wires, that are accidentally formed, or cut wires with a razor blade from the thin foil that is also formed. Wires obtained by this method have

the disadvantage that, owing to fluctuations in their size, it is difficult to make matched junctions with them.

An alternate method of joining the thermocouple wires and attaching the receivers involves welding the thermoelectric wires together by means of a condenser discharge. The details of this procedure are given in the paper cited below.[10]

The receiver may be waxed to the welded thermojunction with Apiezon wax "W." This method of attaching the receiver yields almost the same sensitivity as soldering.

It is easier to construct a multiple-junction thermopile if one large receiver is waxed to the junctions than to undertake the delicate task of soldering separate small receivers to each junction. The electrical insulation between the junctions of a multiple-junction thermopile can be effected by coating each junction with lacquer before applying the wax used for holding the receivers.

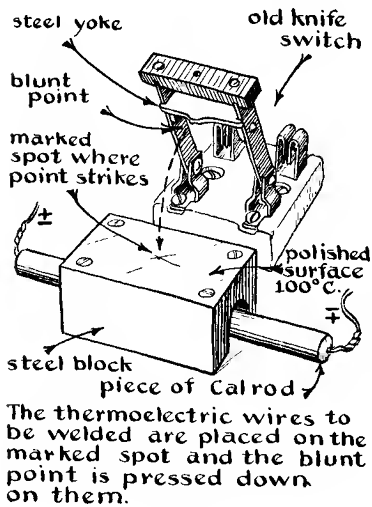


Fig. 17.

Some experimenters construct thermocouples in an order almost opposite to that described. The junction is formed, the receiver is fastened to the junction, and, finally, the thermocouple is soldered to the supporting wires.[11] This procedure is especially suited to the construction of a thermocouple with a small circular receiver, such as may be required for stellar radiometry. For a stellar thermocouple the junction may be soldered with a larger bit of Wood's metal so that there is formed at the junction a small sphere

[10] Cartwright, C. H., *Rev. Sci. Instruments*, *3*, 73 (1932).
[11] Firestone, F. A., *Rev. Sci. Instruments*, *1*, 630 (1930).

of metal, which is then compressed to form a flat receiver of circular shape and of the desired diameter.

Professor Pfund constructs thermocouples by compressing the thermoelectric wires together on a plate of polished steel that is heated to about 100°C.[12] The receiver can be joined to the junction in the same manner. A special device made from a knife switch is used for the manipulation as shown in Fig. 17.

For most applications lampblack is suitable for coating the receiver, but in special cases it may be preferable to use a selective absorbing material for "blackening" the receiver.[13] Thus, a thermopile used for investigation in the far infrared spectrum between 52μ and 152μ might have receivers "blackened" with powdered glass. For work in the visible and ultraviolet spectrum an electrolytic deposit of platinum black is particularly suitable.

The loss of heat by the radiation from a receiver is determined primarily by the emission of the receiver in the spectral region around 10μ (the region in which the maximum emission from a black body at room temperature occurs). The emissive power of platinum black in the region around 10μ is weak (about 20 per cent of that of a black body). Thus, the use of platinum black has the effect of reducing the heat loss L_1, so that the receiver is effectively only one fifth as great as if the receiver were coated with a material that is black for the heat spectrum as well as for the visible spectrum. Besides increasing the sensitivity, this has the further advantage of reducing the theoretical number of junctions required for the best design. Unblackened silver is suggested for receivers to be used in the ultraviolet region.

Fig. 3 illustrates the use of active charcoal for maintaining a high vacuum in the thermopile. An alternate method

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[12] Pfund, A. H., "Radiation Thermopiles," *Rev. Sci. Instruments*, *8*, 417 (1937).

[13] Woltersdorff, W., *Zeits. f. Physik*, *91*, 230 (1934).

Forsythe, W. E., *Measurement of Radiant Energy*, page 210. New York: McGraw-Hill Book Company, 1937.

Pfund, A. H., *J.O.S.A.*, *23*, 375 (1933), *23*, 270 (1933).

Strong, J., *Rev. Sci. Instruments*, *3*, 65 (1932).

involves the use of calcium as a getter. This method has been used by Dr. Pettit of the Mount Wilson Observatory and is quite satisfactory. Its use amounts to replacing the active charcoal in the thermopile in Fig. 3 with fresh calcium filings. These calcium filings are baked out while the tube is connected to the pump. Later, from time to time when the sensitivity of the thermopile falls off, owing to a decay of the vacuum, maximum sensitivity can be re-established simply by reheating the calcium.

The use of sensitive thermopiles. As ordinarily used, the radiant energy focused on the active receiving surface of the thermopile is interrupted periodically to isolate the effect of this radiation from the effect of other radiations falling on the receiver. The excursion of the galvanometer resulting from interrupting the measured beam is ascribed to changes in the temperature of the junctions produced by the radiant energy. Considering that delicate measurements may produce a change in temperature of only 10^{-6}°C., it is necessary to interrupt the light rather accurately to compensate for the first-order drifts which arise owing to a constant warming or cooling of the surroundings of the entire thermopile. As a result, just as much time is required for controlling the zero position of the galvanometer as for determining the deflection produced by the energy being measured.

It is evident that care is required in selecting the best position for the shutter in an optical system. For example, it is required that the change in the radiant energy falling on the thermopile due to closing the shutter should be the same as the change produced by removing the source of the radiations without changing the position of any object "seen" by the thermopile. Otherwise, the variation of radiation from closing the shutter may falsify the measurement. The shutter is to be put before the entrance slit of the spectrometer rather than after the exit slit in order to minimize this possibility.

Compensated thermopiles. While first-order drifts in the galvanometer can be eliminated even for an uncom-

pensated thermopile by properly timing the exposures of the thermopile to the radiant energy, second-order drifts (due to a change in rate of the drift) can be eliminated only by the use of a compensated thermopile. In practice, it is difficult to construct a compensating receiver that will effect the elimination of more than 90 per cent of the galvanometer drift, but further compensation can be achieved by shunting an electrical resistance across the most sensitive of the junctions, either the active or the compensating ones. The junctions to be shunted and the value of the shunt resistance are determined experimentally. When the shunt resistance has the proper value, severe temperature changes of the surroundings of the thermopile housing produce a minimum deflection of the galvanometer. If care has been taken in constructing a compensated thermopile, the shunting resistance will be great enough so that the sensitivity of the thermopile is not appreciably impaired. One method of testing the compensation is to hold a hot soldering iron a few centimeters in front of the thermopile. When, for example, a particular thermopile of the type shown in Fig. 1 was compensated, the galvanometer drift was diminished to a twentieth part of the original drift, and it was reduced further a hundredfold by the shunting resistance.

Ordinarily, the energy to be measured is concentrated on one receiver; the compensating receiver then acts as an external resistance in the galvanometer circuit, and therefore the deflections are somewhat diminished. In most cases the reduction of first- and second-order drifts justifies compensation and the attendant smaller deflections.

By another procedure the image of the exit slit of the spectrometer covers both receivers, while a shutter in front of the entrance slit of the spectrometer obscures first the aperture of the half of the slit focused on one receiver and then the half focused on the other receiver.[14] Thus the area of each of the two receivers is half the area of the slit. Theoretically, this scheme is expected to yield about 40

[14] Badger, R. M., *J.O.S.A.*, *15*, 370 (1927).

per cent more sensitivity than the ordinary compensated thermopile which has the area of the active receiver, as well as that of the compensating one, each equal to the area of the slit. In order to realize this 40 per cent gain in another but less desirable way, the mirror used for concentrating the radiant energy may be tilted periodically, so that the image of the exit slit of the spectrometer covers first one receiver and then the other.

Auxiliary apparatus. Ordinarily a galvanometer having a period of about 7 seconds and a low resistance of about 10 to 15 ohms is used with a thermopile. For making delicate measurements, the wires leading from the thermopile to the galvanometer should be shielded, so that alternating currents will not be induced in them by stray electromagnetic fields. When the wires are not properly shielded, induced alternating currents are, in a sense, rectified by the thermopile, especially by an uncompensated thermopile, and give a spurious galvanometer deflection.

A simple method of measuring the galvanometer response is to observe a well-illuminated scale with a telescope. The galvanometer should be arranged so that the scale is at a distance of about 5 m. A telescope of about 32-power magnification, placed as close as possible to the galvanometer, should be used. With a galvanometer mirror 10 mm in diameter, it should be possible to see the millimeter divisions so clearly on a scale at a distance of 5 m that deflections on the scale can be estimated to a small fraction of a millimeter.

A lack of definition is often erroneously attributed to the galvanometer mirror, but it is usually due to the use of optically imperfect glass for the galvanometer window. However, there is a limit to the definition attainable, because of the finite size of the galvanometer mirror and the effect of diffraction. A simple rule is that the scale distance as measured in meters must not be greater than the diameter of the galvanometer mirror as measured in millimeters. Thus, for a scale distance of 5 m, the galvanometer should be at

least 5 mm in diameter. About $\frac{1}{20}$ mm deflection at a distance of 5 m corresponds to the unavoidable natural fluctuations in the position of the galvanometer due to Brownian motion.

The accuracy with which the position of a cross hair on a millimeter scale can be estimated is much greater than

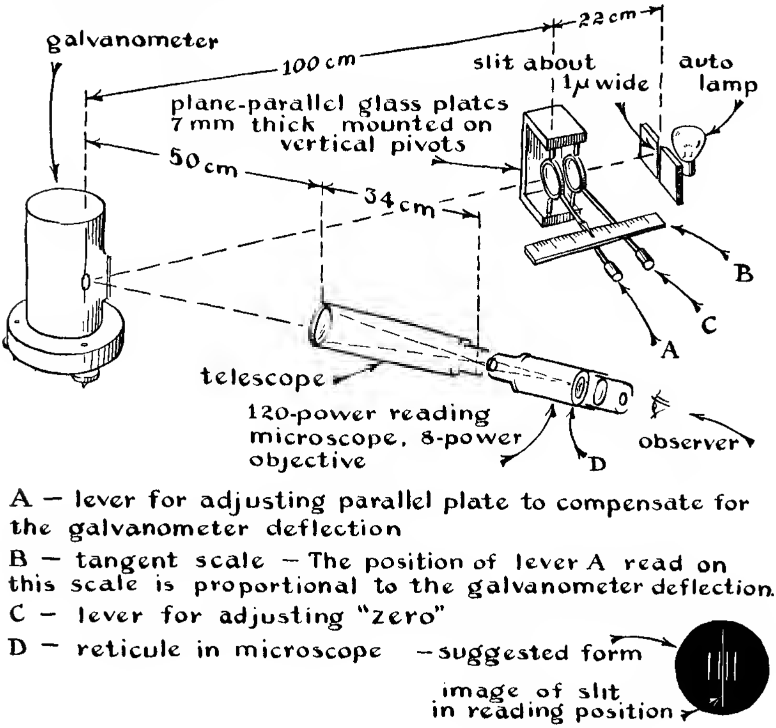

Fig. 18.

might at first be supposed. A standard laboratory experiment for students at the University of Berlin is to estimate the positions of extra marks made on a millimeter scale. All of the extra marks are made on a ruling engine, so that their positions are accurately known. Although the lines are all about $\frac{1}{10}$ mm wide, the student is asked to estimate the position of each extra line to $\frac{1}{100}$ mm. In estimating these positions, a student seldom makes an error of $\frac{1}{10}$ mm,

and an experienced observer will have a probable error for a single reading of about 0.03 mm. Accordingly, it is significant to estimate galvanometer readings to $\frac{1}{20}$ mm.

Fig. 18 shows an ingenious and accurate arrangement used by Professor Czerny for determining the magnitude of small galvanometer deflections.[15]

Relays. A convenient method of reading galvanometer deflections is to use an optical amplifier. Also, when it is desirable to record radiometric measurements photographically, the primary deflections should be amplified by means of some type of relay, and the deflections of a secondary galvanometer recorded on moving photographic paper.

The Moll and Burger thermo-relay may be used for amplifying galvanometer deflections until Brownian motion becomes conspicuous.[16] Other amplifiers include the barrier-layer photocell amplifier described by Barnes and Matossi[17] and the thermopile with two triangular-shaped receivers described by Cartwright.[18]

The Barnes and Matossi type of relay is made by dividing the active surface of a barrier-layer photocell by scratching along a diameter so as to make two contiguous semicircular areas of active surface. The arrangement of this amplifier is illustrated in Fig. 17, Chapter X. Leeds and Northrup produce an amplifying galvanometer and photocell combination of this type.[19]

The above methods of amplifying galvanometer deflections also magnify the drift of the primary galvanometer. This is undesirable. Pfund and Hardy have devised a resonance radiometer, which tends to "ignore" drift and separate it from the response to the measured radiation.[20]

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[15] Czerny, M., *Zeits. f. Physik*, *90*, 468 (1934).
Czerny, M., Heins, H., and Woltersdorff, W., *Zeits. f. Physik*, *95*, 262 (1935).

[16] Moll, W. J. H., *Phil. Mag.*, *50*, 624 (1925). The Moll and Burger thermo-relay is sold by Kipp and Sonen, Delft, Holland.

[17] Barnes, R. B., and Matossi, R., *Zeits. f. Physik*, *76*, 24 (1932).

[18] Cartwright, C. H., *Rev. Sci. Instruments*, *3*, 221 (1932).

[19] Leeds and Northrup Company, Philadelphia, Pennsylvania.

[20] Hardy, J. D., *Rev. Sci. Instruments*, *1*, 429 (1929), *5*, 120 (1934).
Pfund, A. H., *Science*, *2*, 69 (1929).

Their scheme is somewhat elaborate and requires the use of a tuned pendulum shutter, in addition to two identical galvanometers. However, the instrument has advantages, especially when the thermopile is not adequately protected from extraneous thermal effects. Pfund describes the resonance radiometer briefly as follows:

> If primary and secondary galvanometers are underdamped and adjusted to the same period, then, by interrupting the radiation falling on the thermopile with a periodicity corresponding to that of the galvanometers, a condition of resonance is set up. As a class, resonating systems are characterized by high sensitivity for "tuned" periodic disturbances and by indifference to random disturbances.

This indifference to random disturbances unfortunately does not include Brownian motions of the primary galvanometer. Hardy has measured the effect of the Brownian motion on the resonance radiometer and has found that the fluctuations in the deflection of the secondary galvanometer are magnified in accord with theoretical predictions for fluctuations due to Brownian motion.[21] Nevertheless, Hardy feels that delicate measurement to the limit set by these effects is definitely facilitated by the use of the resonance radiometer. The slowness of the resonance radiometer (it takes about 90 seconds to make a measurement) is one of its disadvantages.

Firestone[22] has made an ingenious variation from the Pfund scheme. It depends on charging and discharging a condenser through the secondary galvanometer with a circuit controlled by the amplified thermocouple current. A photocell amplifier is used. Naturally, as the output galvanometer circuit has infinite ohmic resistance, owing to the condenser in the circuit, no net current can flow, and consequently all deflections are excursions about an unchanging zero position.

We have emphasized the importance of using a compensated thermopile to diminish galvanometer drifts as well

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[21] See also Van Lear, G. A., Jr., *Rev. Sci. Instruments*, *4*, 21 (1933).

[22] Firestone, F. A., *Rev. Sci. Instruments*, *3*, 163 (1932).

as to make the circuit electrically insensitive to high-frequency electromagnetic radiations. For the most delicate measurements, it is also necessary to have the galvanometer

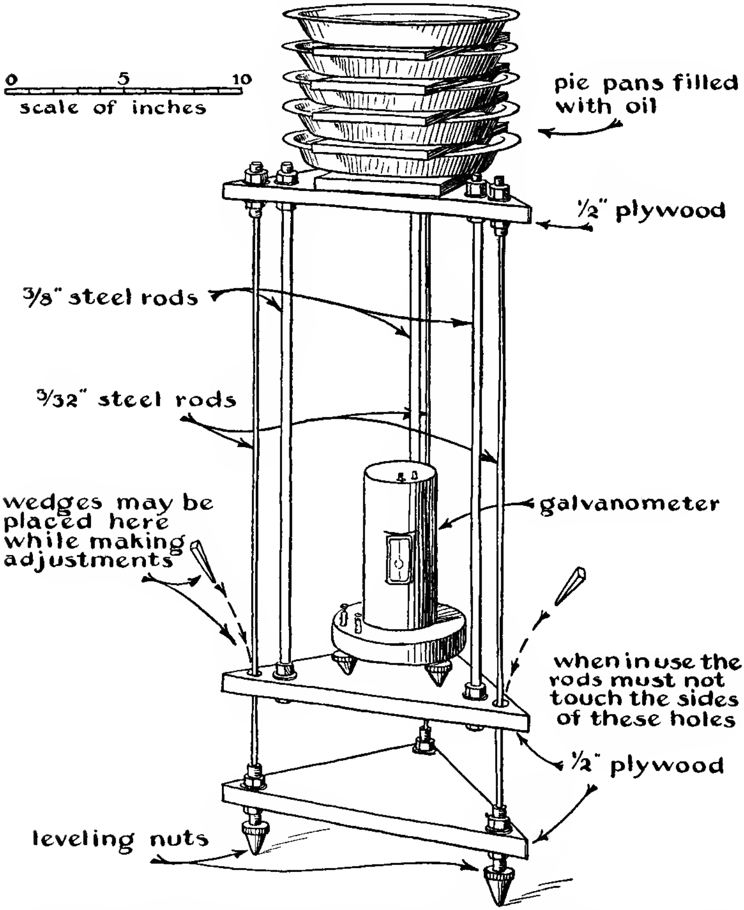

Fig. 19. Vibrationless support for a galvanometer. The plywood triangle, on which the galvanometer stands, should be loaded with lead weights until the natural oscillations have a period of about 2 seconds.

free from mechanical vibrations. This can be accomplished by the use of a vibrationless support such as the type shown in Fig. 19. The description of this vibrationless support is given in Chapter XIV.

Construction of thermojunctions by evaporation and sputtering. There are other applications of thermopiles and thermocouples, such as their use for vacuum manometers, for measuring alternating currents, for measuring sound intensities, for magnifying deflections of a spot of light in thermo-relays, and for total-radiation pyrometers. We cannot go into all these applications in detail, but the present chapter and the references cited should serve to guide an experimenter in these fields. The construction of thermopiles by evaporation and sputtering, however, warrants a description.

Thermopiles made from films of the thermoelectrically active metals, produced by evaporation or sputtering, can be constructed having a very low heat capacity, so low, in fact, that they will respond to the adiabatic heating produced by separate sound waves of 5000 cycles frequency.[23]

One of the metal films used is bismuth and the other is antimony. The foundation on which the metal films are deposited must be extremely thin and strong. For this purpose, glass, mica, or lacquer films are used.

When a soft-glass tube is fused at one end and strongly blown out with air pressure so as to expand and explode a thin bulb, the shattered bulb wall yields fine ribbons of glass about 1 or 2 mm wide and 1 or 2 cm long. These ribbons are of such a thickness as to give interference colors and make a suitable foundation for evaporated thermocouples.

When a mica sheet is rolled upon a stick of about 2 mm in diameter so that one of the principal directions is parallel to the stick, it is subject to shearing forces. These forces produce cleavages, so that when the sheet is subsequently split, bands from 1 to 0.1 mm wide are obtained which, judging from their interference colors, are as thin as or thinner than 1μ.[24]

Films for use as a thermopile base, or for many other

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[23] Harris, L., and Johnson, E. A., *Rev. Sci. Instruments*, *5*, 153 (1934).

[24] This is the technique described in Burger, H. C., and van Cittert, P. H., *Zeits. f. Physik*, *66*, 210 (1930).

purposes, may be made by dropping a thinned solution of lacquer onto the surface of a bowl of dust-free distilled water.[25] Surface tension causes the drop to spread out, forming a liquid film on the water over about half the area of the water surface. The lacquer soon becomes solid as the solvent evaporates. Fig. 20 shows how these films are taken off the water on a metal frame. They are allowed to dry after the peripheral area of the film is pulled back anywhere that it is in contact with the main stretched area. The thickness of film desired is controlled by varying the dilution of the lacquer before it is dropped on the water.

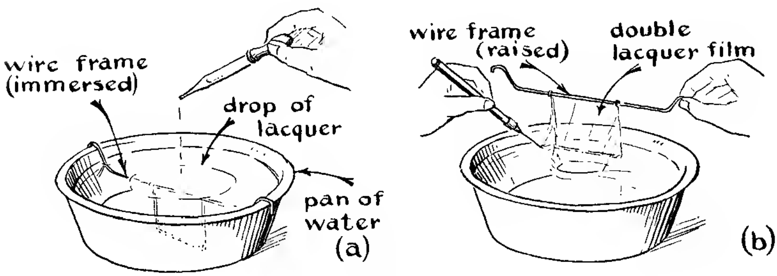


Fig. 20.

Extremely thin uniform films are formed on water cooled to 0°C. Films as thin as 5×10^{-6} cm are obtainable. Double films formed on a frame as illustrated in Fig. 20 are stronger than single films of double thickness, owing to the fact that, in the case of double films, weak areas in one film are seldom opposite weak areas in the second film.

When the thermoelectric metal is deposited on the foundation film by evaporation, the heat of condensation of the metal vapor, as well as the heat radiated by the filament and absorbed by the film, tends to elevate the temperature of the foundation. It is necessary to prevent the temperature of the film from rising to a point at which it might be

[25] Harris, L., and Johnson, E. A., *Rev. Sci. Instruments*, *4*, 454 (1933). They use methyl and ethyl acetate solvent for 2 parts cellulose acetate and 1 part glyptal lacquer at 0° C. to get the strongest films.

Czerny, M., and Mollet, P., *Zeits. f. Physik*, *108*, 85 (1937).

destructive: The films are mounted in the evaporation chamber in contact with mercury or, better yet, in contact with a copper cooling block.

Following the procedure described by Burger and van Cittert[26] bismuth and antimony are used for the thermojunctions, the bismuth being evaporated to form a strip about 1μ thick, while the antimony is evaporated to form a strip of half this thickness. The proper weight of metal to be evaporated is determined by a simple calculation using Eq. 2 in Chapter IV. The area coated with the metal is defined by templates. The bismuth strip, which is evaporated first, is deposited a little beyond the point which is to be the center of the junction, say 0.2 mm or so. Then, the evaporated antimony strip is allowed to overlap the center by an equal amount. The area where the strips overlap forms the junction. The junction is then coated by evaporation with bismuth black, antimony black, or zinc black over a prescribed area, which is defined by baffles.

To form an area to which electrical contact may be established, gold is sputtered or evaporated at appropriate points on the metal films. The connector wires may then be soldered to the gold.

The bismuth crystals formed in the strip by condensation of vapors have their axes perpendicular to the base. This crystal orientation results in a thermoelectromotive force against antimony of 75 microvolts/°C. The optimum crystal orientation, so far unattainable by evaporation, gives a thermoelectromotive force of about twice this value.

Evaporated thermojunctions are especially useful for making the Moll and Burger type thermo-relay. Burger and van Cittert were able to obtain a sensitivity about two and one-half times as great as that obtained with the ordinary rolled Moll and Burger element.

Considerations in thermopile design. The thermopile shown in Fig. 1 and described above can be adapted to meet most of the needs of an experimenter interested in making

[26] Burger, H. C., and van Cittert, P. H., *Zeits. f. Physik*, *66*, 210 (1930).

radiometric measurements. Some experimenters, especially those intending to make extremely delicate measurements, will be interested in the theory for the design of thermopiles. For example, the experimenter designing a vacuum thermopile of a given area has several decisions to make. He must decide which metals to select for the thermocouple wires and determine whether to make few or many junctions. Also, he must decide on the material to be used for coating the receivers. Or, he may wish to design a thermopile to operate at atmospheric pressure.

The equations expressing the theoretical dependence of the galvanometer response on the number of junctions, area of receiver, characteristics of thermoelectric wires, and so forth, have been completely developed.[27] Calculations based on this theory require a knowledge of the characteristics of the thermoelectric wires, namely, their thermoelectric power, electrical conductivity, and heat conductivity. The calculations also require a knowledge of the optical properties of receiving surfaces, such as their emissivity and reflectivity for various wave lengths. With this information, it is possible to design the thermopile which will give optimum response under the obtaining conditions.

The characteristic sensitivity of a thermopile determines its response and, in the theory, this quantity Q is defined as follows:

$$Q = \frac{\sqrt{I^2R}}{\Phi}. \tag{2}$$

Φ is the radiant energy falling on the receivers in unit time, I is the current in the galvanometer-thermopile circuit, and R is the total resistance in this circuit. Q is in effect like an efficiency—the efficiency with which the radiant energy to be measured is converted into galvanometer deflections.

The expression for Q for an uncompensated vacuum thermopile of n junctions in terms of the quantities on which it depends is

[27] Cartwright, C. H., *Zeits. f. Physik*, *92*, 153 (1934).

$$Q = \frac{I\sqrt{R}}{\Phi} = \frac{nP}{\sqrt{R_t + R_g + R_e}}\left[4\sigma\epsilon A T^3 + \frac{n^2T}{R_t}(\sqrt{W_1} + \sqrt{W_2})^2 + \frac{n^2PT}{R}\right]^{-1}, \tag{3}$$

where I is the thermoelectric current in the thermopile-galvanometer circuit, R is the total electrical resistance of the circuit, made up of the thermopile resistance R_t, the galvanometer resistance R_g, and any external resistance R_e. P is the combined thermoelectric power of the thermoelectric wires, expressed in volts per degree centigrade. σ is the Stefan-Boltzmann radiation constant, A the area of the receiver, T the absolute temperature of the receiver, and ϵ its effective radiating power. W_1 and W_2 are the Wiedemann-Franz coefficients of the two thermocouple wires.

The quantity in the brackets represents the total heat losses of the receiver. The middle term in the brackets represents heat loss by conduction through the wires, and the third term represents heat loss due to the Peltier effect. Ordinarily the influence of Peltier heat on the design may be neglected.

The first term in the brackets represents the heat lost by radiation and gas conduction. Where the receiver is not in a high vacuum, gas conduction has the same effect on thermopile design as increasing the magnitude of ϵ and, as we have pointed out before, the use of a receiver with a small emissivity for heat radiation, ϵ, has the effect on thermopile design of decreasing the quantity ϵA.

Fig. 21 illustrates for a vacuum thermopile the way in which Q depends on the values of ϵA, the number of junctions, and the total electrical resistance in the thermopile circuit. With ϵ taken as unity the curves are constructed for $A = 1\ \text{mm}^2$ and $A = 3\ \text{mm}^2$. Furthermore, these curves are for thermoelectric wires made of pure bismuth and wires of bismuth plus 5 per cent tin having a thermoelectric power of 120 microvolts/°C. and Wiedemann-Franz

coefficients of 3×10^{-8} watt ohm/°C.^{2} and 4.2×10^{-8} watt ohm/°C.^{2} respectively. The full curves are for thermopiles having one, two, three, and four junctions, and the dotted

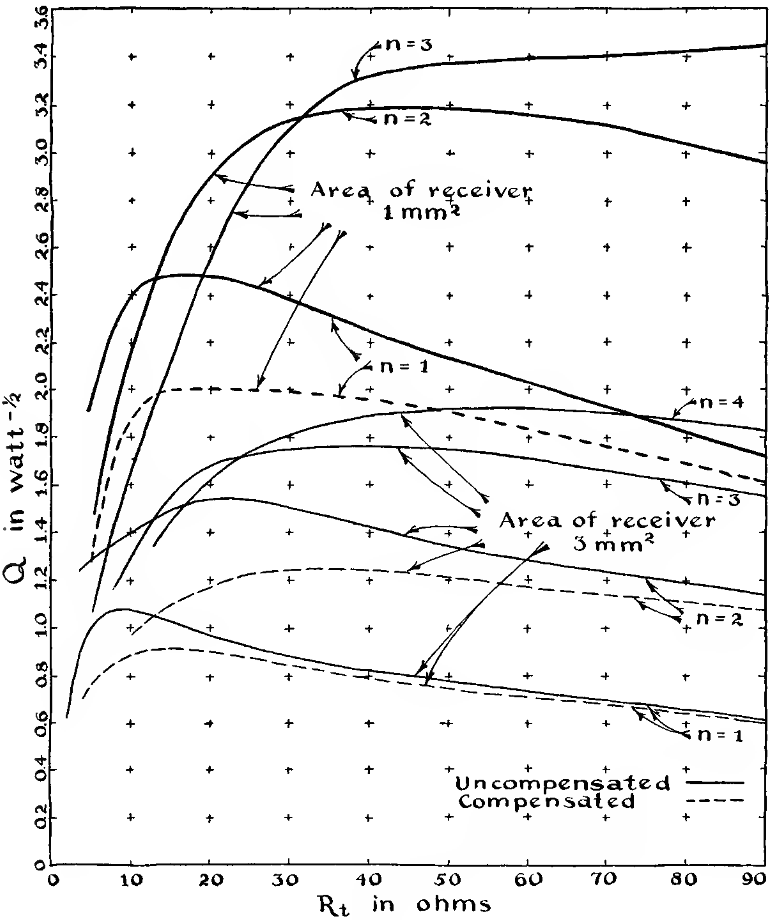


Fig. 21.

curves are for compensated thermopiles having one and two active and compensating junctions respectively.

It is desirable, from a practical point of view, to have a minimum number of junctions to build. The information given in Fig. 21 facilitates making the compromise between

this practical consideration, on the one hand, and the desire to have a maximum sensitivity on the other. From curves in this figure, it is apparent that the energy should be concentrated onto a receiver which is as small as possible.

By reference to Eq. 3 we see that when the third term in the brackets is small in comparison with the first and second terms, the sensitivity, Q, appears to be proportional to the thermoelectric power, P. This is not always the case in practice, and a thermoelectric metal should not be chosen on the basis of the thermoelectric power alone. As a matter of fact, most metals with a high thermoelectric power have an unfavorable Wiedemann-Franz coefficient, which may, in the end, make them even less desirable than metals such as the bismuth alloys, which are convenient to manage.[28]

Sensitivity and minimum energy detectable. When the quantity Q, given by Eq. 2, is combined with the current sensitivity, $d\theta/dI$, and the total resistance of the circuit, R, it yields the composite sensitivity, S, of a thermopile and critically damped galvanometer according to the formula

$$S = \frac{\theta}{\Phi} = \frac{\frac{d\theta}{dI}Q}{\sqrt{R}}. \tag{4}$$

Here θ is the deflection of the galvanometer caused by the radiant energy Φ falling on the receiver in unit time.

It has been customary to compare the sensitivities, S, of the various radiometric instruments. This has led to some confusion in the literature. Actually, in making the most delicate radiometric measurements, we are not interested primarily in the value of S (which can be made as large as desired by the use of an amplifier) but rather in the accuracy with which the radiant energy can be measured in a given

[28] Cartwright, C. H., *Ann. d. Physik*, *18*, 656 (1933). The Wiedemann-Franz coefficient, W, of any metal can be determined by using the empirical formula

$$W = 2.32 \times 10^{-8} + 3 \times 10^{-1}\frac{\rho}{T} \text{ watt ohm/°C.}^2,$$

where ρ is the specific electrical resistivity and T the absolute temperature. For good conductors ρ is small, so that W is the same for all these substances.

time, or, what amounts to the same thing, in the smallest intensity of radiant energy that can be measured in a given time with a given accuracy. The magnitude of this smallest deflection is influenced by disturbances acting on the instruments.

We will designate this smallest deflection that can be measured by a single reading in a time t_0, and with a mean relative error g, by the symbol $\theta_{\text{min.}}$ Until 1926 it was considered that the elimination of the disturbances on which the value of $\theta_{\text{min.}}$ depends was simply a matter of refining experimental technique. Ising was the first to point out that our experimental technique is already advanced far enough so that in many cases $\theta_{\text{min.}}$ is determined by the ever-present Brownian motion fluctuations.[29] If we consider the thermopile system isolated from all disturbances except those produced by Brownian motion of the galvanometer, then the value of $\theta_{\text{min.}}$ is easy to determine. According to the principle of the equipartition of energy, every object with one degree of freedom, such as the moving system of our galvanometer, will possess a definite amount of kinetic and potential energy. The average value of the kinetic energy or potential energy at 19°C. is

$$\tfrac{1}{2}kT = 2 \times 10^{-21} \text{ watt sec.} \tag{5}$$

The average deflection due to the potential energy is involved in the expression

$$\text{Potential energy} = \tfrac{1}{2}K\overline{\theta^2} = \tfrac{1}{2}kT, \tag{6}$$

where K is the torsional constant of the suspension and k is Boltzmann's constant. When a reading is taken, the fluctuations of θ give rise to an uncertainty amounting to $\sqrt{kT/K}$. Therefore, in order to have a probable error of g, a single deflection must be at least $1/g$ times the average fluctuation, or

$$\theta_{\text{min.}} = \frac{1}{g}\sqrt{\frac{kT}{K}}. \tag{7}$$

[29] Ising, G., *Phil. Mag.*, *1*, 827 (1926).

It can be shown that this expression is a general one applicable to any radiometric instrument. Combining Eq. 7 with Eq. 4, we get an expression for the least energy that can be measured:

$$\Phi_{\text{min.}} = \frac{6.6 \times 10^{-11}}{Sg\sqrt{k}} \text{ watt.} \tag{8}$$

In comparing the $\Phi_{\text{min.}}$ of different radiometric instruments, it is necessary to specify not only the accuracy factor g, but also the time t, to be taken for measuring a deflection. In the case of a galvanometer, this is because the value of $d\theta/dI$ depends on t_0. The value of S also depends on t_0 for other radiometric instruments. It is not correct to assume, as is usually done, that the value of $\Phi_{\text{min.}}$ varies with the square of the period of the deflecting device. As a matter of fact, in the case of a thermopile and critically damped galvanometer, the value of $\Phi_{\text{min.}}$ is proportional to the square root of the period time of the galvanometer.[30]

The $\Phi_{\text{min.}}$ of a thermopile and galvanometer can be expressed in terms of the factor g, the Q of the thermopile, and the period of the galvanometer, as follows:

$$\Phi_{\text{min.}} = \frac{1.1 \times 10^{-10}}{gQ\sqrt{t_0}} \text{ watt.} \tag{9}$$

With the values of Q given by the curves in Fig. 12 it is therefore possible to estimate the minimum energy falling on the receiver in unit time that can be measured with a proposed apparatus. It is to be observed that the sensitivity of the galvanometer does not enter Eq. 9. Eq. 9, however, does imply that the deflections are measured either directly or with the help of an amplifying device to the limit set by Brownian motion.

General summary of the work on thermopile design. The remainder of this chapter will be devoted to a summary of the results of experimental and theoretical investigations made by one of the authors, C. Hawley Cartwright, on the

[30] Cartwright, C. H., *Physics*, *1*, 211 (1931).
Czerny, M., *Ann. d. Physik*, *12*, 993 (1932).

relative merits of the different radiometric instruments, and in addition will present some general (although not necessarily final) conclusions resulting from these studies.

Vacuum microradiometers can be made which will measure less energy, $\Phi_{\text{min.}}$, than the best vacuum thermopiles used with a separate galvanometer. This advantage is not sufficient to offset the practical advantage of greater flexibility of the thermopile with separate galvanometer.

Vacuum bolometers and vacuum thermopiles have at present practically the same limit, Φ_{min}. If a material with better characteristics than nickel were available for the construction of the bolometer strip, this situation would be altered.

Radiometers will not respond to as small energies, $\Phi_{\text{min.}}$, as thermopiles. The direct comparisons made by the author, especially in Berlin and Brussels, between vacuum thermopiles and radiometers yield results in favor of vacuum thermopiles. Radiometers are usually much more sensitive than thermopile and galvanometer combinations, owing to the use of a much lighter moving system than is possible with a galvanometer. Brownian motions are, however, increased, so that they more than offset the advantage of the larger primary deflections.

A question of considerable importance and one which bears on the above conclusions is the following: Why is there often considerable variation in the sensitivity of vacuum thermopiles, in fact, sufficiently large variations to be responsible for many of the publications that have appeared on improving thermopiles? The answer is that many vacuum thermopiles are not constructed with the maximum possible sensitivity, for the following reasons:

1. The sensitivity of a thermopile depends on the skill exercised in its construction.

2. For the most part, thermopiles have been constructed without first calculating the proper design or, if this is done, without dependable information on the physical properties of the materials used.

3. A sufficiently high vacuum is not always used. A properly designed and constructed thermopile should be about twenty times more sensitive in high vacuum than in air, and, on increasing the vacuum from 10^{-3} to 10^{-6} mm of mercury, the sensitivity should be doubled.

4. The thermoelectric power of the bismuth and bismuth-alloy wires is often less than 120 microvolts/°C. Slight impurities can greatly influence the thermoelectric power of bismuth by influence on crystal orientation, and so forth. For example, the thermoelectric power of pure bismuth relative to copper changes from 57 to 107.7 microvolts/°C. for different crystal orientations.[31]

5. The influence of deviations of the properties of bismuth, and especially bismuth alloys, from the predictions of the Wiedemann-Franz law is generally neglected, with the result that thermoelectric wires with a resistance which is too small are used so that the sensitivity falls on the left-hand steep part of the curves corresponding to those shown in Fig. 21.

Actually, the ultimate attainable sensitivity for a thermopile is limited by the unfavorable departure from the Wiedemann-Franz law of the thermoelectric metals that possess a high thermoelectric power. However, if this were not the case, it is interesting to note that the thermoelectric power itself would limit the sensitivity. From Eq. 3 we see that for a thermoelectric power of 250 microvolts/°C. the heat loss due to the Peltier effect is equal to the heat loss due to conduction through the wires. Although the possibility exists of finding better thermoelectric metals than bismuth and the alloy of bismuth and 5 per cent tin, it seems rather improbable that much progress will be made in this direction.

It is well to keep in mind that although tin has ten times less specific electrical resistance than bismuth, an alloy of bismuth and 5 per cent tin has twice the specific electrical resistance of pure bismuth. This should be considered when better thermoelectric metals are being sought. Bismuth

[31] Bridgman, P. W., *Am. Acad., Proc.*, *63*, 347 (1927–1928).

itself is an unusually favorable metal for thermopiles, not only because it has a relatively high thermoelectric power, but also because it is a pure metal element having a small specific electrical resistance and does not depart greatly from the Wiedemann-Franz law.

In order to improve the sensitivity of thermopiles, there is the possibility of using them at low temperatures, where Q can be increased, owing to a greater thermoelectric power, a more favorable Wiedemann-Franz ratio, and less radiation loss from the receivers. However, liquid-air thermopiles have several practical disadvantages.[32]

[32] Cartwright, C. H., *Rev. Sci. Instruments*, *4*, 382 (1933).

CHAPTER IX

Optics: Light Sources, Filters, and Optical Instruments

Divisions of the spectrum. The electromagnetic spectrum divides naturally into the region for which the eye is sensitive, the infrared region, with frequencies below those which we perceive as red, and the ultraviolet region, with frequencies higher than those which we perceive as violet. These regions are defined roughly by the wave lengths given in Table I. In the text we will use microns for expressing wave length in the infrared and Ångströms for expressing wave length in the visible and ultraviolet. The visible region includes less than one octave of frequency, while the so-called infrared region embraces at least nine octaves and the ultraviolet embraces five or six octaves.

Light sources. *The sun.* The sun naturally comes first in consideration of light sources. Its use is recommended

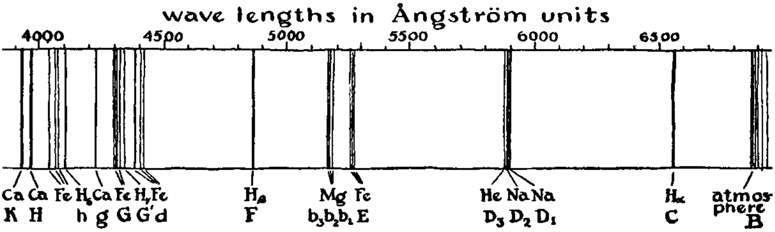


Fig. 1.

for many experiments because of its brightness and because in the Fraunhofer lines it contains numerous convenient wave-length landmarks. The Fraunhofer lines, which are conspicuous in the spectrum exhibited by a good pocket spectroscope, are shown in Fig. 1.

The energy distribution in the solar spectrum, as observed through the atmosphere, is closely approximated by that of a black body at 5400°K. The luminous efficiency of the

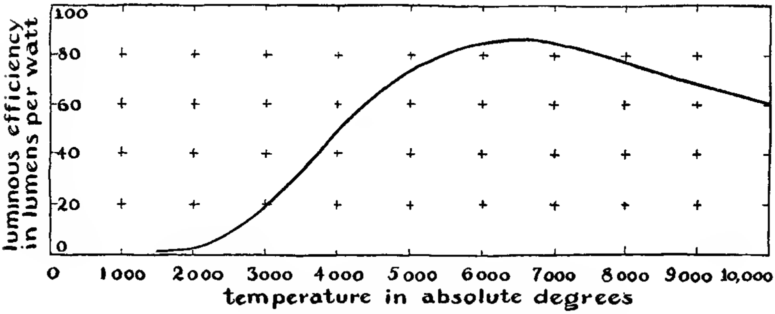


Fig. 2.

sun is about 80 lumens/watt. As will be seen in Fig. 2, this is nearly as high an efficiency as it is possible to attain with a heated body.

TABLE I

DIVISIONS OF THE ELECTROMAGNETIC SPECTRUM

Spectral Region	Wave-Length Limits
Extreme ultraviolet	500 Å to 2000 Å
Ultraviolet	2000 Å to 4000 Å
Visible: Violet	4000 Å to 4460 Å
Visible: Indigo	4460 Å to 4640 Å
Visible: Blue	4640 Å to 5000 Å
Visible: Green	5000 Å to 5780 Å
Visible: Yellow	5780 Å to 5920 Å
Visible: Orange	5920 Å to 6200 Å
Visible: Red	6200 Å to 7200 Å
Near infrared	0.72μ to 20μ
Intermediate infrared	20μ to 40μ
Far infrared	40μ to 400μ

A heliostat or coelostat is required if a beam of sunlight is to be maintained in a fixed direction in the laboratory. Heliostats are obtainable from scientific supply companies.

Their mirrors, which are usually silvered on the back, should be recoated on the front surface with aluminum if it is desired to obtain in the reflected sunlight the full range of solar spectrum down to the atmospheric cutoff at approximately 3000 Å.

The details of construction for a home-made coelostat are shown in Figs. 3 and 4. This coelostat may be driven by

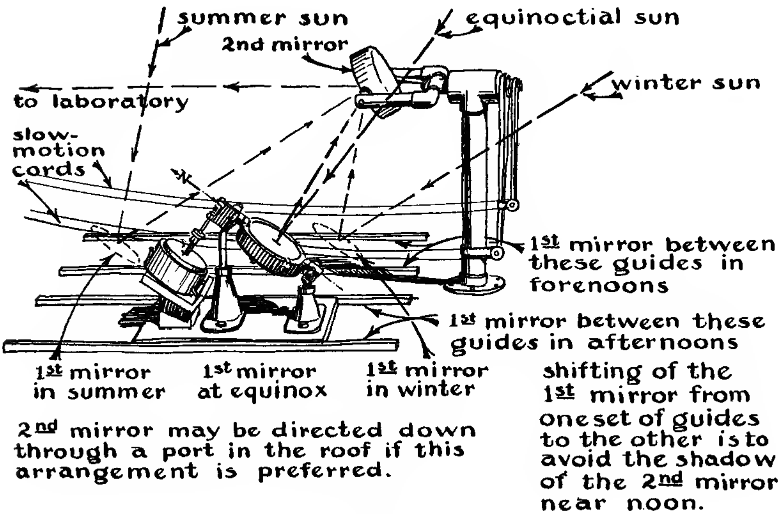


Fig. 3.

the works of an alarm clock as shown; it may also be driven by a Telechron clock. The secondary mirror of the coelostat has controls operated by cords for making adjustments.

Tungsten lamps. Tungsten lamps are the most convenient laboratory source of white light. Their efficiency is about 11 lumens/watt for the nitrogen-coiled filament type.

The differences of spectral energy distribution of various tungsten-filament lamps are illustrated in Fig. 6, Chapter XI. The spectrum of emission of the filament is limited in the ultraviolet and infrared by the transmission of glass. With glass bulbs $\frac{1}{4}$ mm in thickness, the spectrum extends from about 3100 Å in the ultraviolet to 3μ in the infrared.

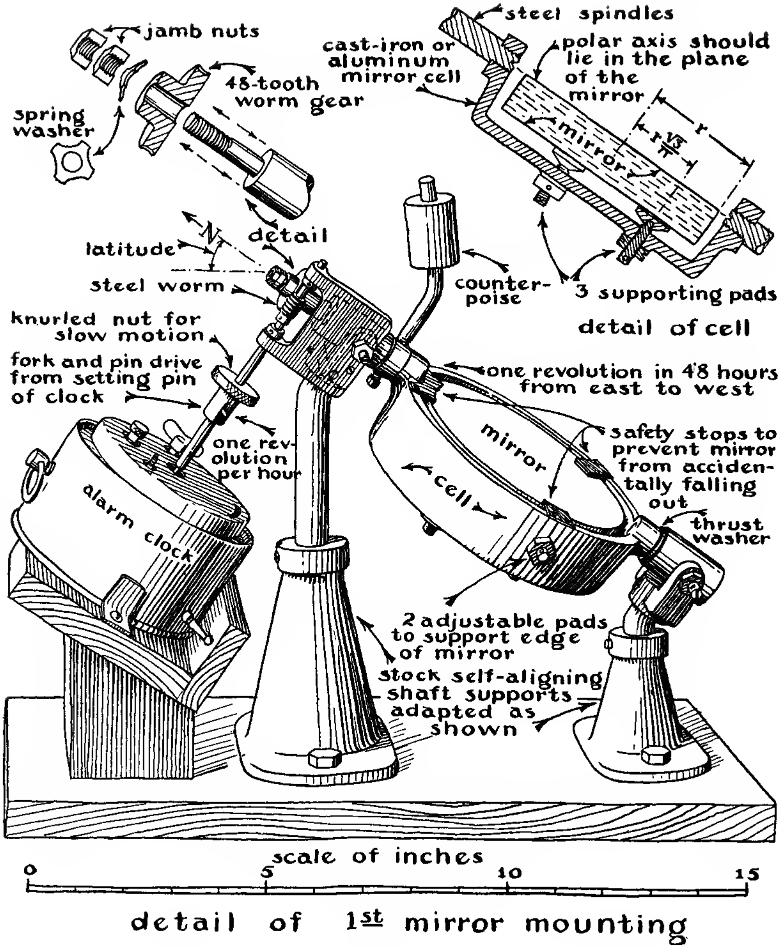


Fig. 4.

Two tungsten lights convenient for many purposes in the laboratory are shown in Fig. 5. The one shown on the left is a projection lamp. It requires 6 volts and 18 amperes. An autotransformer or high-capacity storage battery serves as power source. The battery is, of course, preferred when constancy and steadiness of the emission are important.[1] The

[1] The autotransformer is as satisfactory as the battery when it is energized by the output of a Raytheon voltage regulator.

lamp shown at the right has a straight filament. It is useful as a galvanometer lamp. Both of these lamps are obtainable commercially.[2]

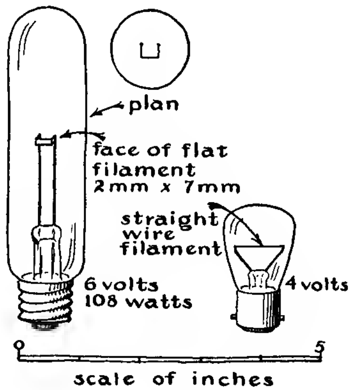
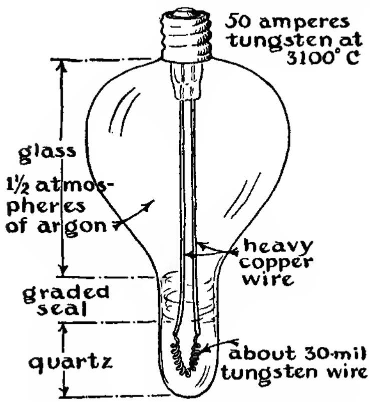


Fig. 5.

A trade-mark on the end of a tungsten lamp bulb, when it interferes with the light emission of the filament, may be removed by polishing with rouge and felt or with wet crocus cloth.

A lamp[3] with a quartz bulb for absorption spectra is shown in Fig. 6. The bulb contains argon at $1\frac{1}{2}$ atmospheres pressure. The tungsten operates at about 3100°C. and gives a continuous emission spectrum extending into the ultraviolet to 2500 Å. At the operating temperature, the vapor pressure of tungsten is appreciable, and it would normally blacken the quartz part of the bulb. However, vertical convection currents of argon gas carry the evaporated tungsten molecules upward from the filament, so that they are not deposited on the quartz but rather on the upper glass part of the bulb, where they do not impair the usefulness of the lamp.



continuous spectrum to 2500Å

Fig. 6.

Welsbach mantle.[4] This refractory mantle was formerly used extensively for house

[2] These lamps may be obtained from the General Electric Company, Nela Park, Cleveland, Ohio.

[3] This lamp is supplied by the Philips Laboratory, Eindhoven, Holland.

[4] Ives, H. E., Kingsbury, E. F., and Karrer, E., "A Physical Study of the Welsbach Mantle," *Frank. Inst., J.*, *186*, 401, 585 (1918).

illumination and is now used in gasoline lamps. It is brought to incandescence in the outer hot surface zone of a Bunsen burner type of flame, where it assumes a temperature nearly as high as the Bunsen flame temperature. The mantle is composed of thorium oxide with 0.75 to 2.5 per cent cerium oxide added to increase its visible emissivity. This addition of cerium oxide plays much the same role as the sensitizer for a photographic plate; that is, it introduces an absorption band in a desired spectral region without materially affecting the optical properties elsewhere. The effect of the cerium oxide is to make the emission in the green 30 per cent greater than that of a black body at 1800°C., whereas the emissions in the red and blue correspond closely to 1800°C. color temperature.[5] The near infrared emissivity is less than 1 per cent from 0.7μ to about 6μ, and the incapacity of the mantle to radiate heat in this important region accounts for its high temperature. For the spectrum beyond 10μ the mantle again has an emissivity greater than 75 per cent. The mantle is an excellent laboratory source for those long wave-length infrared radiations.[6]

Barnes suggests heating the mantle with a sharp oxygen flame striking it at a grazing angle.[7] This gives it a higher temperature, and also the elongated heated section produced is properly shaped for illuminating the slit of a spectrometer. More recently, Pfund has devised an arrangement to combine both electric and flame heating, allowing the attainment of even higher temperatures.[8]

Nernst glower. Nernst filaments are composed of zirconium dioxide powder with about 15 per cent yttrium oxide powder.[9] For operation on alternating current, flexible platinum lead wires are later cemented to each end

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[5] Forsythe, W. E., *J. O. S. A.*, *7*, 1115 (1923).

[6] Rubens, H., *Deutsch. Phys. Gesell., Verh.*, *7*, 346 (1905); *Ann. d. Physik*, *18*, 725, (1905), *20*, 593 (1906); *Phys. Zeits.*, *6*, 790 (1905), *7*, 186 (1909).

[7] Barnes, R. B., *Rev. Sci. Instruments*, *5*, 237 (1934).

[8] Pfund, A. H., *J. O. S. A.*, *26*, 439 (1936).

[9] Nernst, W., and Bose, E., *Phys. Zeits.*, *1*, 289 (1900).

Nernst glowers are obtainable from Stupakoff Laboratories, 6627 Hamilton Avenue, Pittsburgh, Pennsylvania.

of the refractory tube with a mixture of the oxide powders and zirconium chloride as a binder. For operation on direct current, the manner of attaching the electrodes is more complicated. The Nernst lamp normally operates at around 2000°K. Its spectrum extends well into the ultraviolet and infrared. However, beyond 15μ its emission is said to be inferior to the emission of the Globar heater.

At one time the Nernst glower offered great promise for commercial lighting, owing to a luminous efficiency of 6 lumens/watt as compared with 3 lumens/watt for the carbon filament. However, the modern incandescent lamp with a coiled tungsten filament in an atmosphere of nitrogen, having an efficiency of 11 lumens/watt, entirely changed matters. The use of the Nernst light is now confined to the laboratory. Here its usefulness depends upon the fact that it is operated in air and has a convenient form (cylinder 0.4 to 0.6 mm in diameter and 1 to 2 cm long) for focusing on the slit of a spectrometer. Griffith has described details of construction for making Nernst filaments.[10]

Since the Nernst lamp has a negative temperature coefficient of resistance, it must be stabilized with external resistance or, better, with a ballast lamp having an iron-wire filament mounted in hydrogen.[11] The iron wire of this lamp runs at a faint red glow; its remarkable current-stabilizing effect in an atmosphere of hydrogen at 30 to 100 millimeters pressure is shown in Fig. 7. Such a ballast lamp consumes 10 or 15 per cent of the total power needed for operating the Nernst filament.

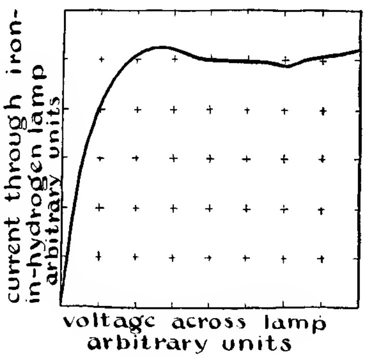

Fig. 7.

[10] Griffith, H. D., *Phil. Mag.*, *VI*, *50*, 263 (1925).

[11] For the theory of the hydrogen ballast lamp, see Busch, H., *Ann. d. Physik*, *64*, 401 (1921).

Globars. The Globar is a rod of bonded silicon carbide about $\frac{5}{16}$ inch in diameter and about 10 inches long. The ends fit into aluminum cup electrodes. A potential of 100 volts across the rod brings it to an orange or yellow heat. It can be operated in air at a temperature above 1000°C., although at temperatures around 2000°C. the carbide dissociates and carbon is vaporized or oxidized, leaving silicon, or, in the presence of air, silicon dioxide. A protective layer of thorium dioxide sintered to the outside of the Globar with thorium chloride as binder will allow of temperatures in excess of 2000°C.[12] A suitable mounting for the Globar is shown in Fig. 8.

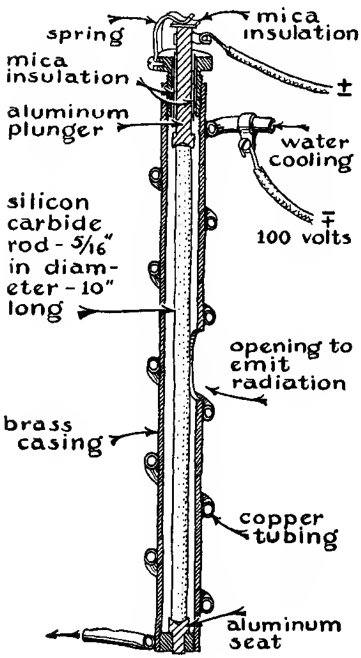

Fig. 8.

Carbon arcs. The carbon arc is useful as a laboratory light source. Ordinarily, the positive carbon is mounted horizontally. An 8-mm positive carbon is consumed at the same rate as a 6-mm vertical negative carbon. Accordingly, if carbons of this size are used, they may be fed into the arc automatically by clockwork.

The carbon arc requires at least 40 volts to operate it. Higher voltage increases the size of the positive crater without materially affecting its surface temperature.

The character of the light emission from the ordinary carbon arc may be influenced by the addition of metallic salts as cores in the carbons. (Magnesium fluoride is often used to get a white arc.) The spectral distribution of the

[12] I am indebted to C. H. Cartwright for this information.

carbon arc with cored carbons is illustrated in Fig. 9. This is a curve of galvanometer deflections against wave length, as determined with a quartz monochromator (shown in Fig. 32) and cesium oxide photocell. (See Chapter X.) The slit widths were the same for all wave lengths. This curve does not correct for the transmission of the image-forming lens (shown in Fig. 5, Chapter XI) which was used to focus the light. Without this lens the spectrum would have extended well into the ultraviolet.

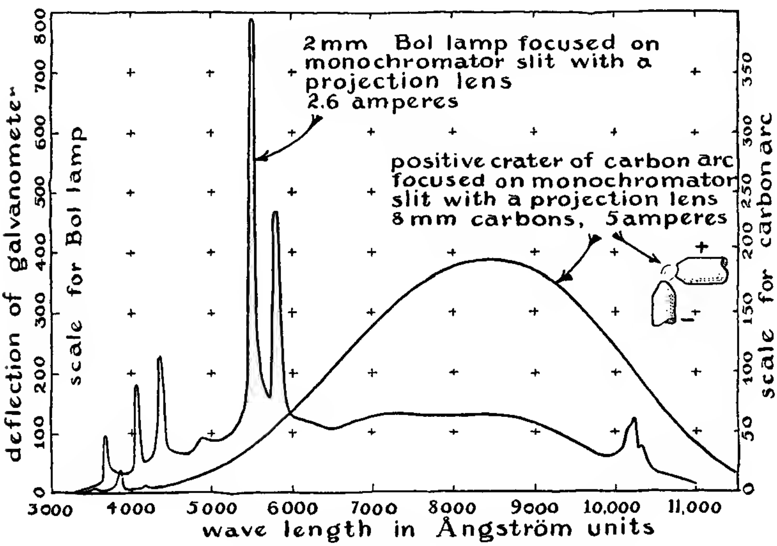

Fig. 9.

The ordinary carbon arc has a crater brightness of about 13,000 candles/cm² and an efficiency of about 35 lumens/watt. The Sperry Gyroscope Company has produced an arc that uses special shields to confine the current to a definite boundary around the rotating crater.[13] This arc is about six times as bright as the ordinary arc.

Lummer has succeeded in obtaining extreme temperatures in the carbon arc by operating it in an inert atmosphere

[13] Benford, F., *Trans. Soc. Motion Picture Eng.*, *24*, 71 (1926).

under high pressure. Under a pressure of 22 atmospheres he was able to obtain temperatures of 7600°K., considerably in excess of the solar surface temperature. The surface brightness reported for this temperature was 280,000 candles/cm². The attainment of such temperatures and brightness is difficult.

A technique of measuring. For the preliminary study of a spectrum plate, a technique of measuring and recording data which is neat and avoids confusion is illustrated in Fig. 10. This procedure employs an enlarged print of the original spectrum plate to identify the iron or other reference lines appearing in the eyepiece of the comparator. To facilitate this identification, the wave lengths of the iron lines are written in the margin of the print. Also, the print serves as a permanent record of the appearance of the spectrum as well as a record of the data of measurement.

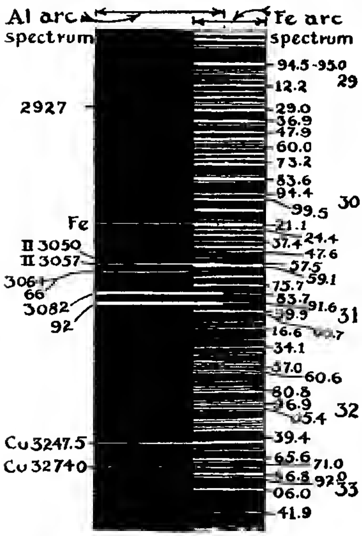

Fig. 10.

First, the wave lengths of conspicuous iron comparison lines, which are to be used as reference lines in the measurement, are written in the margin. The original plate has the same appearance in the eyepiece of the comparator as the enlarged print; thus it easily serves to identify the comparison lines. After the wave length of each unknown line is determined by interpolation, it is recorded on the clear margin of the print as shown at the left in Fig. 10. Notes may also be added in this margin when the wave lengths are later identified by reference to Kayser's tables.[14]

[14] Kayser, H., *Tabelle der Hauptlinien der Linienspektra aller Elemente.* Berlin: Julius Springer, 1926.

Iron arcs. The iron arc is used in the laboratory by the spectroscopist as a source of ultraviolet light and also as a standard comparison source. Its spectrum has been thoroughly studied, and the wave lengths of the lines, as well as the influence of pole and pressure effects on them, are well known.[15]

An iron arc developed by Pfund[16] suitable for use in the laboratory is shown in Fig. 11. An iron oxide bead is placed on the lower electrode for stabilizing the arc. If the

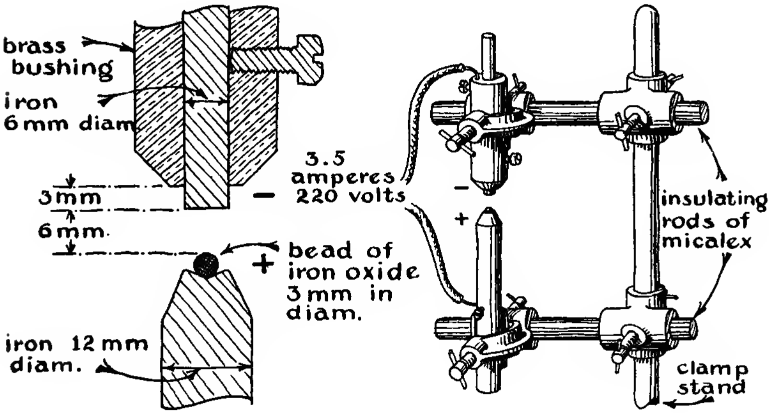

Fig. 11.

upper electrode is a graphite rod, the arc is even more stable than it is with an iron electrode.[17] The arc can be started by rubbing a carbon across the gap.

Low-pressure mercury arcs. The low-pressure mercury arc is a convenient laboratory light source.[18] It gives several strong lines in the visible, ultraviolet, and near infrared

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[15] See the following:

Babcock, Harold D., *Astrophys. J.*, *66*, 256 (1927), *67*, 240 (1928).

St. John, Chas. E., and Babcock, Harold D., *Astrophys. J.*, *46*, 138 (1917), *53*, 260 (1921).

[16] Pfund, A. H., *Astrophys. J.*, *27*, 298 (1908).

[17] The National Carbon Company produces a spectroscopic grade of pure graphite. The pure carbon arc exhibits only one line in the visible or the ultraviolet spectrum. This line is 2478 Å.

[18] For a description of a simple, home-made, low-pressure arc, see Pfund, A. H., *Astrophys. J.*, *27*, 299 (1908).

spectra. These lines are far enough apart to be separated with filters. (See Table XI.)

The ultraviolet spectrum of the arc in a fused quartz tube extends to about 2000 Å. The energy at the extreme short wave-length limit produces ozone in the air. The ozone formation, however, becomes weaker and weaker as the lamp is burned, owing to changes in the transmission limit of the quartz. Finally the ozone formation practically ceases. Baly has found that such changed quartz will emit a green phosphorescence and will regain its original transparency if it is heated in the blast burner.[19]

The Cooper-Hewitt type of mercury light has a brightness of about 2.3 candles/cm^2. The ordinary Cooper-Hewitt illuminating lamp has a tube 4 feet long and about 1 inch in diameter. It is a convenient light source for many experiments when an extended source is desired, as for observing Haidinger's and Newton's fringes. To get uniform illumination over an extended area, drafting linen is hung below the lamp.

In glass the Cooper-Hewitt lamp does not, of course, emit all of the ultraviolet spectrum. Recently this arc has been put on the market, made with a tube of Corex red-purple glass which suppresses the visible radiation (except 4046) and transmits the near ultraviolet. In this form it is excellent for therapeutic use.

The commercial hot quartz vacuum arc is much more brilliant (350 candles/cm^2) than the Cooper-Hewitt lamp discussed above. The ordinary hot quartz lamp is not of a convenient form for use in the laboratory, but it is now available in the form of a vertical straight quartz tube constructed especially for laboratory use.[20] These laboratory arcs are equipped with rectifiers, so that they may be operated on either alternating or direct current.

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[19] Baly, E. C. C., *Spectroscopy*. New York: Longmans, Green and Company, 1927.

[20] This lamp and the one discussed above are obtainable from the Cooper-Hewitt Electric Company, Hoboken, New Jersey.

High-pressure mercury arcs. Harries and Hippel[21] have described a high-pressure mercury lamp which is now commercially available.[22] This is illustrated by Fig. 12. The lamp is mounted in a nearly light-tight case—a very convenient construction for use in the laboratory. The lamp is made of uviol glass or quartz, with or without added cadmium to obtain the red cadmium 6438 Å line. Schott glass filters are also supplied for isolating the yellow, green, blue, violet, or ultraviolet lines.

The spectrum of the high-pressure lamp exhibits considerable continuous background. Accordingly, the spectral

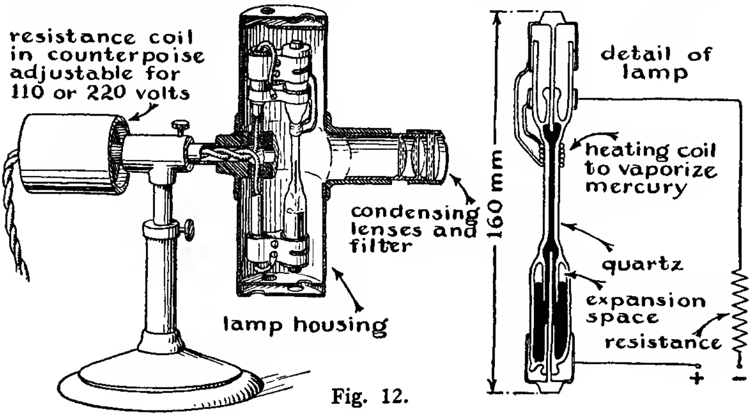

Fig. 12.

purity obtainable with it by the use of filters is not as great as it is with the low-pressure arc. The emission, however, is very steady, especially when the lamp is operated on storage batteries.

Cornelius Bol of Stanford University (formerly of the Philips Laboratory, Eindhoven, Holland) has developed a so-called super-high-pressure mercury arc.[23] The discharge

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[21] Harries, W., and Hippel, A. v., *Phys. Zeits.*, *33*, 81 (1932).

[22] This lamp is obtainable from Schott und Gen., Jena, Germany. Their agent in this country is Fish-Schurman Corporation, 250 East 43rd Street, New York.

[23] Bol, C., *Das Licht*, *5*, 84 (1935); *Ingenieur*, *50*, 91 (1935).
Barnes, B. T., and Forsythe, W. E., *J. O. S. A.*, *27*, 83 (1937).
Dushman, S., *J. O. S. A.*, *27*, 1 (1937). A bibliography of high-efficiency light sources is given.

which produces the high pressure is started, however, by argon at a pressure of 2 or 3 cm of mercury. The operating potential for the lamp is around 500 volts. Heat generated by the argon discharge volatilizes the liquid mercury exposed in the lamp until a pressure of mercury gas of about 200 atmospheres is attained. On account of the high ultimate pressure, the lamp must be made of a thick-walled capillary tube as shown in Fig. 13. The tungsten electrodes project beyond the reserve mercury in order to guide the discharge down the central part of the tube. In the center, temperatures of 8600°C. and brightness values several times greater

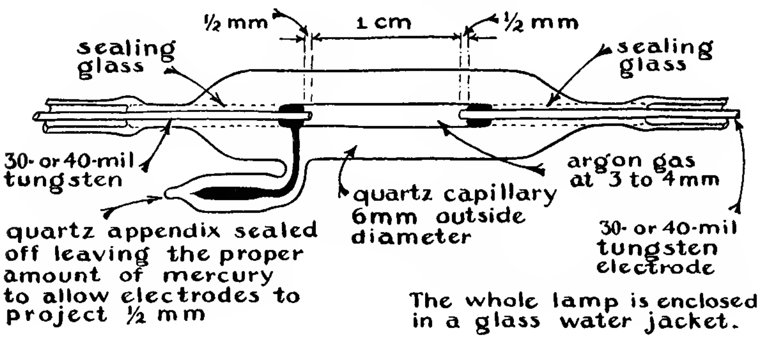


Fig. 13.

than the brightness of molten tungsten are attained. For example, a lamp operating on 640 volts at a pressure of 200 atmospheres has a brightness of 180,000 candles/cm^2 and a luminous efficiency of 79 lumens/watt. The emission of a Bol lamp is shown in Fig. 9. (See also Table II.)

The inside surface of the quartz capillary probably attains a temperature in excess of the critical temperature of mercury, so that no liquid mercury can condense. The mercury-gas envelope around the hot central core of the arc absorbs the resonance line emitted in the core, and at the obtaining pressure and temperature the resonance line is so broad that its absorption extends over the major part of the ultraviolet spectrum (to 2700 Å).

The electrodes are sealed in the Bol lamp with a new

glass. A lamp of convenient size for use in the laboratory has the electrodes spaced 1 cm apart. It is first filled with 2 cm pressure of gaseous argon and then with liquid mercury until the 30-mil tungsten wires project about $\frac{1}{2}$ mm beyond the mercury at each end. A 640-volt transformer is suitable for operating the light. It is connected in series with the arc and a suitable choke coil. When the arc is shorted out, the choke will draw about 3.4 amperes from the transformer.[24]

A "cold," low-pressure mercury-vapor lamp is shown in Fig. 14.[25] This lamp employs a few millimeters pressure of hydrogen, argon, or one of the other noble gases as a starting gas. Heat developed by the discharge in the noble gas soon distills mercury vapor from small globules of the liquid metal.

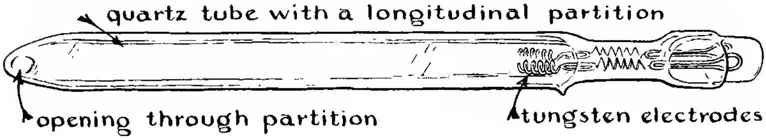


Fig. 14.

The potential for operating the lamp is obtained from a sign transformer or from a storage battery and spark coil. This lamp is only about one tenth as brilliant in the visible as the Harries and Hippel lamp, but its emission at 2536 Å is manyfold greater. In fact, about 80 per cent of its total emission is in the resonance line.

The resonance line from the mercury lamp shown in Fig. 14 is so strong that the mercury vapors, rising from a globule of liquid mercury held in the hand, cast a strong shadow on a fluorescent screen.[26] With a 3-mm Corex red-purple filter to suppress the visible spectrum, this lamp is ideal for exciting the fluorescence of minerals.

This type of mercury light is very useful in the laboratory.

[24] The Bol lamp must be operated surrounded with a stream of cooling water.

[25] This lamp is obtainable from the Reed and Miller Company, 16 South Raymond Street, Pasadena, California.

[26] See Leighton, W. G., and Leighton, P. A., *Jour. of Chem. Ed.*, *12*, 139 (1935).

When neon is used instead of argon as the starting gas, this single source yields a series of strong lines well distributed over the spectral range from 2536 Å to 10,140 Å. The gap in the mercury spectrum between 6907 Å and 10,140 Å is filled by a series of neon lines around 8300 Å.[27]

Filters for use with the various mercury arcs to yield monochromatic light are discussed in a later section.

Other gaseous discharges. Commercial sodium arcs are now available. They are confined in a special glass container that is not attacked by the metal vapor.[28] These arcs operate inside a clear Dewar flask and afford a large-area source of monochromatic light which is particularly suited to many laboratory tests and demonstrations. The characteristics of this and the Bol lamp are given in Table II.

TABLE II

CHARACTERISTICS OF SUPER-HIGH-PRESSURE MERCURY LAMP AND SODIUM LAMP

Item	Sodium Lamp	Mercury Lamp
Pressure (atmospheres)	10^{-5}	200
Current density	0.4	280
Cross section (cm²)	1.43	0.0075
Candles/cm²	10 to 20	1.8×10^5
Vapor temperature (°C.)	280	8600
Light output (lumens/watt)	68	78

Heller, G., *Philips Techn. Rev.*, *1*, 2 (1936).

Mercury lamp: 1400 watts and water cooled, 1.3 amperes, 2 mm cross section.

Sodium lamp: 100 watts in a clear Dewar flask.

Pyrex is not attacked by sodium as readily as are soft glasses, and by fusing borax or boric acid to the inside surface, its resistance to the alkali metal can be further in-

[27] For wide monochromator slits, the tungsten lamp is a much richer light source in this region than the argon discharge.

[28] Buttolph, L. J., *Am. Illum. Eng. Soc., Trans.*, *30*, 147 (1935). For similar lamps using other metallic vapors, see Alterthum, H., and Reger, M., *Das Licht*, *3*, 69 (1933).

creased.[29] Magnesia crystals are not attacked by vapors of the alkali metal, and they may be used for experiments in which sodium, at higher temperatures and pressures, is to be confined behind windows transparent to both the ultraviolet spectrum and the infrared spectrum.[30]

The ultraviolet spectrum obtained from a hydrogen discharge tube is continuous, extending from the short wavelength emission limit of incandescent tungsten toward shorter wave lengths to the limit of transmission of quartz. This hydrogen continuum is most effectively excited by sources of the type developed by Duffendack and Manley, Smith and Fowler, Munch, and Jacobi.[31] These sources excite the spectrum with thermoelectrons emitted from a hot cathode.

Capillary discharge tubes filled with many different elementary gases are now available commercially.[32]

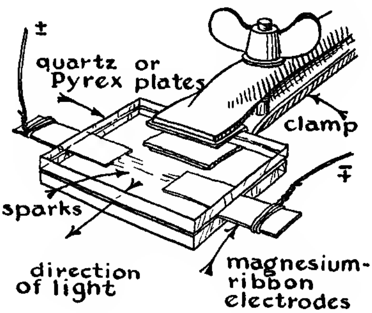


Fig. 15.

Sparks. To obtain the spark spectrum characteristic of the materials composing the electrodes, it is necessary to use a condenser of sufficient capacity to give an explosively noisy spark. Either a transformer or an induction coil can be used as the source of potential. A spark between magnesium electrodes, especially if it is confined between glass

[29] See Chapter XIV.

[30] Brice, R. T., *Rev. Sci. Instruments*, *8*, 209 (1937).
Strong, J., and Brice, R. T., *J. O. S. A.*, *25*, 207 (1935).

[31] Duffendack, O. S., and Manley, J. H., *J. O. S. A.*, *24*, 222 (1934).
Duffendack, O. S., and Thomson, K. B., *J. O. S. A.*, *23*, 101 (1933).
Herzberg, G., *Ann. d. Physik*, *84*, 553 (1926).
Jacobi, G., *Zeits. f. techn. Physik*, *17*, 382 (1936).
Lau, E., and Reichenheim, O., *Zeits. f. Physik*, *73*, 31 (1931).
Lawrence, E. O., and Edlefsen, N. E., *Rev. Sci. Instruments*, *1*, 45 (1930).
Munch, R. H., *Am. Chem. Soc., J.*, *57*, 1863 (1935).
Smith, A. E., and Fowler, R. D., *J. O. S. A.*, *26*, 79 (1936).

[32] These tubes may be obtained from the Central Scientific Company, Chicago, Illinois, and A. D. Mackay, 198 Broadway, New York City.

plates, is very brilliant. Such a light source, shown in Fig. 15, is useful for shadow photographs of bullets in motion, and so forth, and for the photography of sound waves by the Schlieren-methode.[33] The duration of the illumination from the magnesium spark can be made extremely short.

Flames. Flames such as the Bunsen flame, which are almost colorless, give characteristic emission spectra when volatile metallic vapors are introduced. The metals most commonly used to obtain monochromatic or nearly monochromatic light are given in Table III.

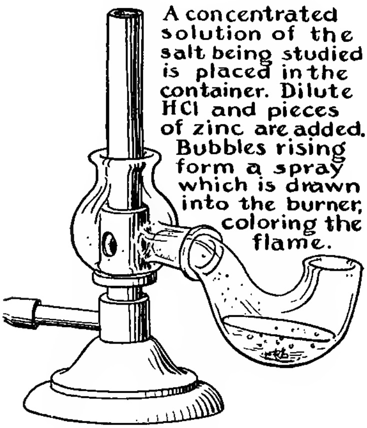


Fig. 16.

Sodium light may be obtained by wrapping asbestos, soaked in sodium chloride, around the tip of the Bunsen burner tube. Another method of introducing the salts into the flame is illustrated by the device shown in Fig. 16. A neodymium filter may be used to absorb the emission of sodium vapor and at the same time transmit the red emission lines from potassium or lithium vapors. To obtain the metallic thallium spectrum, a bead of the metal, fused in a platinum-wire loop, is touched to the edge of the Bunsen flame. The bead is introduced just far enough to obtain the desired rate of evaporation. If the bead is held too far inside the flame, it boils away rapidly. Inasmuch as thallium is a poisonous metal, a high concentration of the vapors in the room should not be allowed. Also, sodium, potassium, and lithium vapors may be introduced into a Meker burner flame by placing a small globule of fused sodium chloride, potassium chloride, or lithium chloride on the grill of the Meker burner.

[33] Wood, R. W., *Physical Optics*, page 93. New York: The Macmillan Company, 1934.

The ultraviolet. The portion of the ultraviolet spectrum treated here will be limited to the wave-length range 2000Å to 4000 Å.[34] In the long-wave half of this region between 4000 Å and 3000 Å many substances are transparent, including mica, celluloid, diamond, Canada balsam, ether, glycerin,

TABLE III

FLAME SPECTRA

Vapor	Wave Length of Emission Lines
Sodium	5890 Å, 5896 Å
Potassium	7665 Å, 7699 Å
Lithium	6708 Å
Thallium	5350 Å

acetone, turpentine, xylene, and in thin layers, many ordinary glasses. (See Table IV.) For the entire region from 4000 Å to 2000 Å the list of materials is not so great. It includes rock salt, potassium chloride, fluorite, magnesia, lithium fluoride, alum, gypsum, sugar, calc-spar, water, ethyl alcohol, glacial acetic acid, liquid ammonia, fused and crystalline quartz, and cellophane. (For the transmission of cellophane see Table V.)

Prisms, lenses, and mirrors for the ultraviolet. Only a few of the substances mentioned above are suitable for making prisms and lenses. Fluorite and quartz make excellent prisms. They can be combined to make achromatic lenses. But the scarcity of fluorite of good optical quality in large sizes makes these achromats very expensive. A combination of quartz and rock salt is sometimes used for making achromats. Recently, synthetic alkali halides and magnesium oxide have become available in large pieces, and these, together with other synthetic substances, will no doubt become important for constructing ultraviolet optics.

[34] For a general treatment of ultraviolet radiations, see Luckiesch, M., Holladay, L. L., and Taylor, A. H., *Frank. Inst., J.*, *196*, 353 (1923).

The optical constants of some of these materials for the visible spectrum are given in Table VI.

Concave aluminized mirrors are now used for ultraviolet optical systems. They have the same focus for ultraviolet as for visible light, and therefore they can be adjusted visually.

TABLE IV

TRANSMISSIONS OF GLASS (5 MM THICKNESS) IN THE ULTRAVIOLET

Wave Length (Å)	Bausch and Lomb Condenser Glass (%)	Schott Glass BK-7 (%)	Vita Glass (%)	Schott Uviol (%)
3300	82	83	86	93
3200	55	68	78	86
3150	35	56	72	81
3100	20	42	64	74
3050	..	24	54	66
3000	..	..	45	59

TABLE V

SPECTRAL CHARACTERISTICS OF CELLOPHANE—PER CENT TRANSMISSION AT INDICATED LINE

Standard Colorless Cellophane

Type	2334	2800	3132	3342	3663	4078	4359	4600	5200	5400	5800	6500
P. T.	60	69	73	79	84	86	87	88	90	90	90	90
M. T.	10	43	84	82	84	90	90	90	90	90	90	90

Standard Plain-Colored Cellophane

Type	2537	2800	3132	3342	3663	4078	4359	4600	5200	5400	5800	6500
Red	0	0	0	0	0	0	0	0	0	2	18	86
Dark green	9	31	28	20	7	0	6	14	47	44	22	12
Dark blue	25	39	38	38	51	71	78	66	43	29	12	7

This table was supplied by E. I. duPont de Nemours and Company, Wilmington, Delaware.

TABLE VI

INDEX OF REFRACTION OF SYNTHETIC MATERIALS

Material	C 6563	D 5893	e 5461	F 4861	g 4358
Fused quartz	1.4567	1.4587	1.4604	1.4634	1.4669
CaF_2	1.4325	1.4338	1.4349	1.4369	1.4395
LiF	1.3906	1.3922	1.3930	1.3943	1.397
KCl	1.4870	1.4901	1.4929	1.4981	1.5043
KBr	1.5544	1.5590	1.5631	1.5709	1.5806
KI	1.6569	1.6655	1.6721	1.6853	1.7025
MgO	1.7337	1.7378	1.7412	1.7475	1.7550
Plexiglas	1.4856	1.4881	1.4902	1.4938	1.4992
Lucite	1.4916	1.4945	1.4967	1.5008	1.5064

Filters for the ultraviolet. Thin metal films are among the most interesting filters for the ultraviolet. The transmission band exhibited by silver and the alkali metals is associated with a gap lying between the region where the reflection is ascribed to the effect of free electrons (on the long wave-length side of the gap), and the region where reflection is ascribed to bound electrons (on the short wave-length side). In silver, this gap at 3160 Å is approximately 100 Å wide. It is much wider than this for the alkali metal films.

Potassium films may be used as a filter for isolating ultraviolet radiations. The full transmission of potassium in the ultraviolet begins at 3000 Å for films of a thickness just sufficient to be opaque in the visible to sunlight. R. W. Wood has studied this phenomenon and describes how these films can be formed on a quartz-glass bulb cooled to liquid air temperatures.[35] Unfortunately, films prepared as he describes are only permanent at temperatures considerably below room temperature. O'Bryan, however, has shown how potassium may be deposited between quartz-glass plates to give films permanent even at the elevated temperature of

[35] Wood, R. W., *Phys. Rev.*, *44*, 353 (1933).

boiling water.[36] The transmission of these thicker films begins at about 3350 Å, becomes about 25 per cent at 2500 Å, and decreases to a little below this value as the wave length 2000 Å is approached. The transmission of such a potassium film is illustrated by Fig. 17.

Fig. 17. Transmission of a potassium film.[36]

Bromine vapor can also be used as a filter. It is transparent to the ultraviolet rays. A layer of saturated bromine vapor 5 cm thick at room temperature is opaque to blue light and nearly opaque to green light, as one can readily see by interposing a bottle containing a little liquid bromine

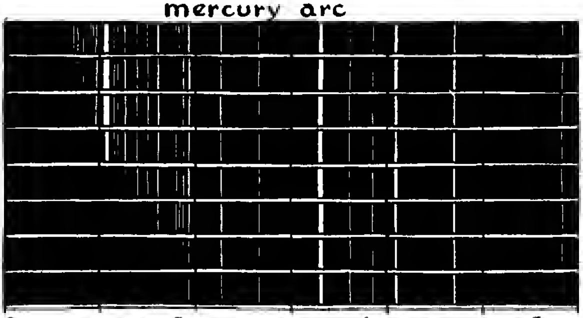


Fig. 18. Transmission spectra of various materials. After Williamson, R. C., *Phys. Rev.*, *21*, 111 (1923).

between a mercury lamp and a pocket spectroscope. The ultraviolet transmission of bromine begins at 3800 Å, and the vapor is quite transparent to the spectrum from wave length 3500 Å down to at least 2345 Å.

[36] O'Bryan, H. M., *Rev. Sci. Instruments*, *6*, 328 (1935).

A 5-mm layer of a solution of nitrosodimethylanalin (10 mg to 100 cc water) has about the same transparency as the bromine vapor.[37]

A filter of 14 g pure, iron-free nickel sulphate crystals and 10 g pure cobalt sulphate crystals dissolved in 100 cc distilled water is opaque to the visible spectrum but transparent

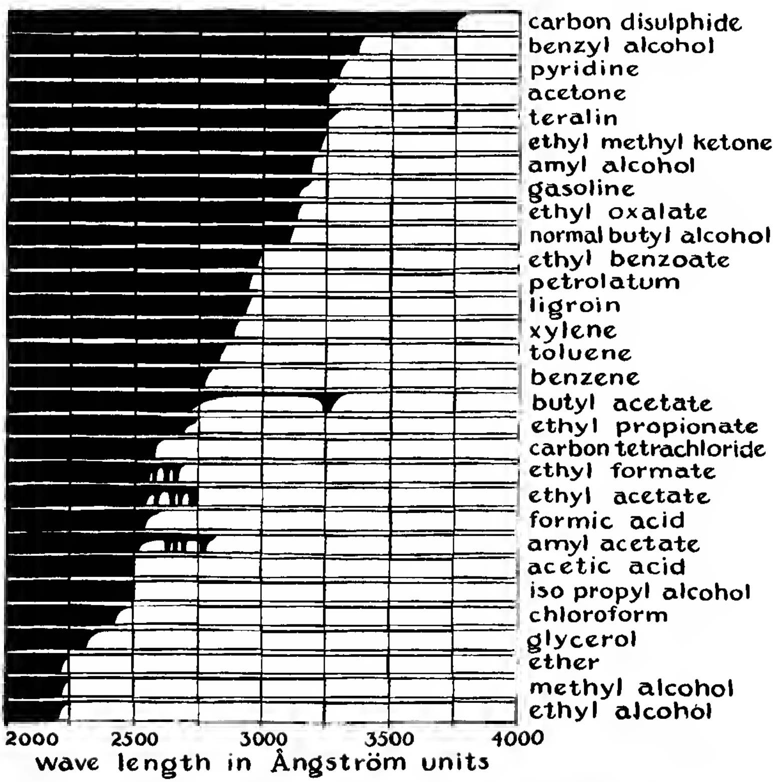


Fig. 19. Transmission of various liquids. After Brode, W. R., *J. Phys. Chem.*, *30*, 56 (1926).

in the ultraviolet below 3300 Å. In layers 3 cm thick this filter transmits 3.5 per cent of the 3342 Å mercury line and 96 per cent of 3126 Å line, and it is transparent as far down in the ultraviolet as 2300 Å.[38]

[37] Wood, R. W., *Phil. Mag.*, *5*, 257 (1903).
[38] Bäckström, H. L. J., *Naturwiss.*, *21*, 251 (1933).

The ultraviolet transmission limit for mica is at about 2800 Å for 0.01 mm thickness. Mica of this thickness is completely opaque at wave lengths below 2600 Å.

The transmissions in the ultraviolet of some other materials are illustrated in Figs. 18 and 19.

Polarization of the ultraviolet. The new sheet polarizers[39] made of herapathite are opaque to ultraviolet light. (See Fig. 38.) Although the calcite of Nicol prisms is transparent to 2000 Å, the Canada balsam used for cementing them is not transparent in the ultraviolet at wave lengths below about 3000 Å. For cementing optical surfaces to be used in the ultraviolet, glycerin, castor oil, or dextrose sugar should be used. A Wollaston prism may be used to polarize light in the ultraviolet when its parts are properly cemented.

The infrared. The infrared spectrum extends from 7600 Å, or 0.76μ, to about 400μ. A thermopile or radiometer is generally used for measuring infrared radiation. As the operation of these instruments depends on thermal effects produced by the radiation, the infrared spectrum is often referred to as the heat spectrum. The infrared radiations are emitted by heated bodies. Ordinarily, heated bodies are used as laboratory sources for the infrared spectrum.

It is convenient to divide the heat spectrum into three regions: The near infrared, from 1.1μ to 20μ; the intermediate infrared, from 20μ to 40μ; and the far infrared, from 40μ to 400μ. The spectroscopic significance of the near infrared is that the characteristic frequencies of gases which fall in this region generally arise from molecular oscillations, whereas the characteristic frequencies which fall in the visible and ultraviolet regions arise in general from electronic oscillations. On the other hand, in the far infrared the characteristic frequencies of gases arise from molecular rotation and molecular bending. In the case of crystals the characteristic frequencies in the near infrared

[39] Land, E. H., *Frank. Inst., J.*, *224*, 269 (1937).
Freundlich, H., *Chemistry and Industry*, *56*, 698 (1937).

are generally interatomic oscillations within the chemical radicals that exist as units in the crystal, while frequencies in the far infrared are due to oscillations of the positive ions (or radicals) of the crystals relative to the negative ones.

The intermediate infrared spectral region from 20μ to 40μ was formerly closed to investigation on account of the lack of transparent substances to be used for making windows and prisms. There are now available, however, a transparent paraffin of high melting point,[40] and large synthetic crystals of the alkali halides which are transparent in the range 20μ to 40μ.[41]

Prisms, windows, lenses, and mirrors for the infrared. The important prism materials for the infrared are listed in Table VII. These materials are not ordinarily combined to

TABLE VII

TRANSMISSION OF MATERIALS FOR INFRARED RADIATIONS

Material	Useful Transmission Limit in the Infrared (μ)
Glass	2.2
Quartz	3.5
CaF_2	8.5
NaCl	15
KCl	21
KBr	29

form achromatic lenses for focusing the infrared rays; mirrors which are much more satisfactory are used. Even spherical mirrors are useful for the less exacting work, since the slits in infrared spectroscopy can never be set as fine as

[40] Kellner, L., geb. Sperling, *Zeits. f. Physik*, *56*, 215 (1929). The paraffin in question is Kurlbaum, M. P., 68° to 72°C.

[41] Bridgman, P. W., *Am. Acad., Proc.*, *60*, 307 (1925), *64*, 19 (1929).
Korth, K., *Zeits. f. Physik*, *84*, 677 (1933).
Kyropoulos, S., *Zeit. f. anorg. allgem. Chem.*, *154*, 308 (1926).
Ramsperger, H., and Melvin, E. H., *J. O. S. A.*, *15*, 359 (1927).
Stober, F., *Zeits. f. Krist.*, *61*, 299 (1925).
Strong, J., *Phys. Rev.*, *36*, 1663 (1930).

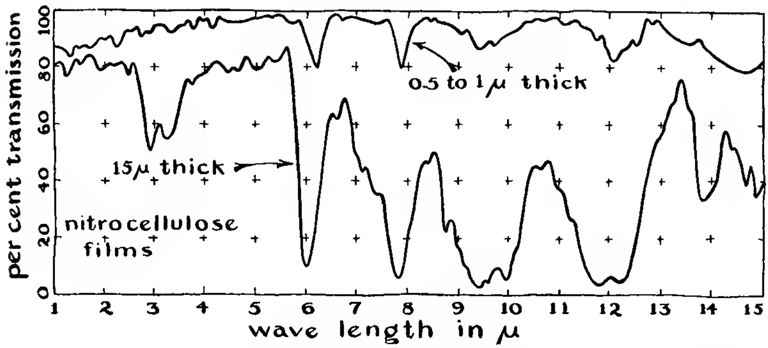


Fig. 20. After Barnes, R. B., and Bonner, L. G., *J.O.S.A.*, *26*, 433 (1936).

they can in the other spectral regions, in which photography can be applied.[42]

Materials useful for windows on absorption cells and vacuum radiometric devices are listed in Table I, Chapter VIII. (See also Figs. 20, 21, 22.) Of these materials the high-melting-point paraffin is of special interest, since it is one of the few materials opaque to the near infrared spectrum and transparent to the long wave lengths. Soot is another such material. Although it is quite opaque in the visible, soot is translucent for the heat spectrum.

The reflection of most metals such as silver, speculum, and aluminum is high in the infrared. The reflectivity for wave

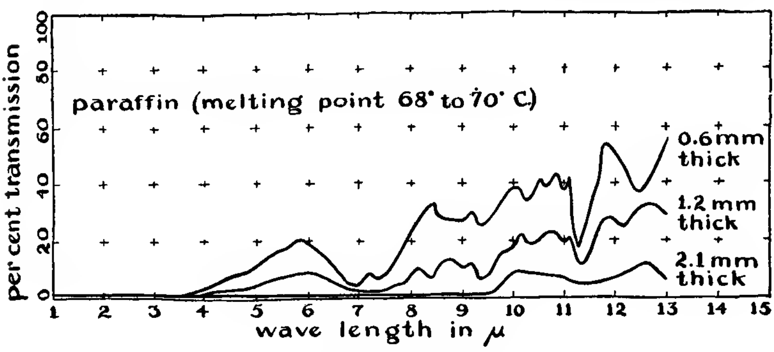


Fig. 21. After Barnes, R. B., and Bonner, L. G., *J.O.S.A.*, *26*, 433 (1936).

[42] Strong, J., *Phys. Rev.*, *37*, 1661 (1931).

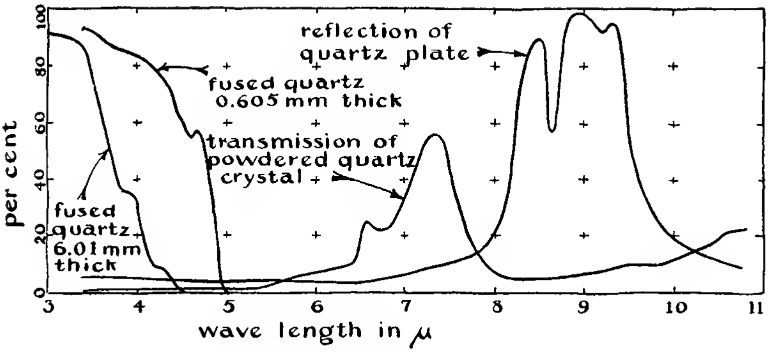


Fig. 22. Infrared transmission and reflection of quartz. After A. H. Pfund.

lengths longer than about 4μ can be calculated from the electrical conductivity of the metal by the expression

$$R_\lambda = 1 - 0.365\sqrt{\rho/\lambda}, \tag{1}$$

where ρ is in ohms mm^2/m and λ is in microns.

Reflection of crystals. Residual rays. Crystals exhibit so-called bands of "metallic" reflection at certain wave lengths where the reflection coefficient, usually of the order of 5 per cent, approaches 100 per cent. This property of crystals was first observed by E. F. Nichols.[43] The bands of high reflectivity exhibited by quartz, for example, are shown in Fig. 23.

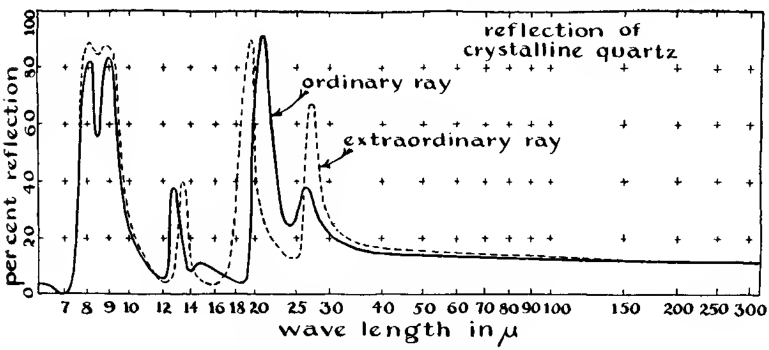


Fig. 23. After H. Rubens.

[43] Nichols, E. F., *Ann. d. Physik*, *60*, 401 (1897); *Phys. Rev.*, *4*, 297 (1897). Rubens, H., and Nichols, E. F., *Ann. d. Physik*, *60*, 418 (1897); *Phys. Rev.*, *4*, 314 (1897).

Quartz (for the ordinary ray) exhibits two strong bands, one at 8.9μ and one at 20.8μ. Rock salt has only one band, at 52μ.

Multiple reflections from crystals are employed to isolate narrow bands of monochromatic radiation from the heat spectrum. For example, if the spectrum from a heated body is reflected once from a rock-salt crystal surface, the energy at wave lengths about 52μ are reflected while those radiations elsewhere, especially in the short-wave spectrum, where the reflection is nonmetallic, are attenuated about

TABLE VIII

Number of Reflections	Crystal Mirrors	Filter (3 mm paraffin in each case)	Wave Length (μ)	Frequency ($\sim$/cm)	Energy (cm of deflection; scale at 3 m)
4	Quartz	1 cm KCl	20.7	483	44
3 1	Fluorite Metal	5 mm KCl	23	435	18
2 2	Fluorite Calcite	3 mm KBr	27.3	366	42
4	Calcite	None	29.4	340	95
3 1	Fluorite Metal	0.4 mm quartz 1.2 mm KBr	32.8	305	2.6
3 1	Aragonite Metal	0.4 mm quartz	41	244	1.6
4	NaCl	2 mm quartz	52	192	5.2
4	KCl	2 mm quartz	63	159	2
4	KBr	2 mm quartz	83	120	1.6
4	KI	2 mm quartz	94	106	1
4	TlBr	2 mm quartz	117	85	1.7
4	TlI	2 mm quartz	152	66	1

twenty times. In spite of this attenuation by a single reflection, the energy in the 52μ band may still be much less than the integrated energy reflected at other wave lengths. After a second reflection, however, the short-wave spectrum is again attenuated about twenty times, or four hundred times altogether, while the energy in the band of waves around 52μ is little affected. Accordingly, after four or five reflections the only radiations remaining, the so-called residual rays, are those of the 52μ band.

The use of these successive reflections is a standard procedure for obtaining monochromatic bands of radiation in the far infrared. The crystals used for obtaining various wave lengths are listed in Table VIII. We shall describe the apparatus used for obtaining residual rays in a later part of this chapter.

Special absorbers for the near infrared. Water is transparent from wave lengths greater than 0.2μ in the ultraviolet throughout the visible spectrum. (See Fig. 24.)

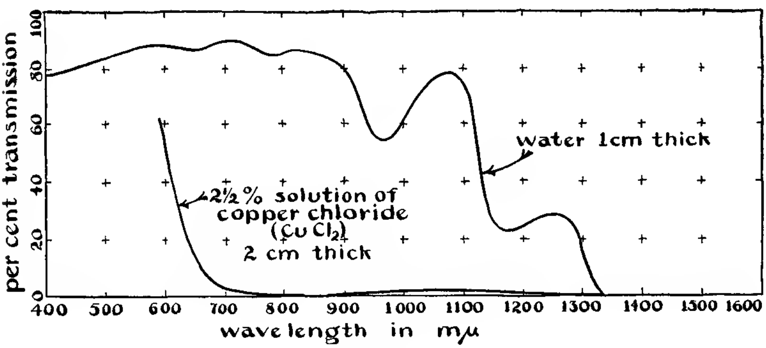


Fig. 24.

However, it is opaque in the heat spectrum for all rays beyond the limits λ_0 for thickness τ_0, as given in Table IX.

A water filter is often used to absorb the heat rays that are emitted when a carbon arc, the sun, or a tungsten lamp is used as a light source. The use of a water filter prevents the cracking of lantern slides with heat, burning of photo-

TABLE IX

TRANSMISSION LIMITS OF WATER IN THE INFRARED FOR THE SOLAR SPECTRUM

τ_0	λ_0 in μ
1 mm	2.4
1 cm	1.5
10 cm	1.2
10 m	0.9
100 m	0.6

Fowle, F. E., *Smithsonian Miscellaneous Collections*, *68*, 49 (1917).
Schmidt, W., *Meterolog. Zeitsch.*, *25*, 321 (1908).

graphic film, overheating of microscope objectives, or excessive heating of polarizing Nicols.

The addition of cupric salts to water results in increased absorption of the infrared. The absorption for the infrared is illustrated in Fig. 24 for a 2-cm cell containing cupric chloride.[44]

Manufactured glass filters such as Aklo glass and the Schott filters BG17 and BG19 are designed to remove the heat

TABLE X

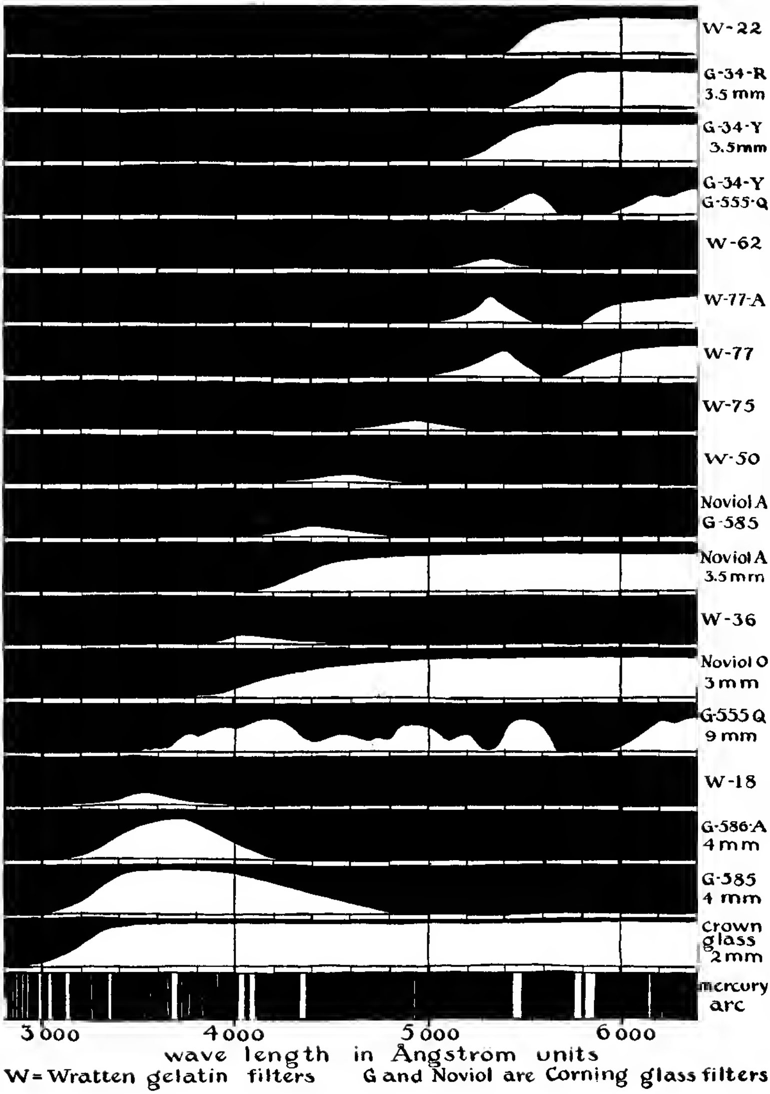
TRANSMISSION OF AKLO HEAT-RESISTING GLASS (2 MM THICKNESS) FOR THE LIGHT OF A VACUUM MAZDA LAMP (2360°K.)

Filter	Total Radiation (%)	Visible Radiation (%)
Extra Light Shade No. 395	40	83
Light Shade No. 396	21	75
Medium Shade No. 397	11	64
Dark Shade No. 398	4	42

Glass Color Filters, Corning Glass Works, Corning, New York.

[44] Absorption of water: Nicholson, Seth B., and Pettit, Edison, *Astrophys. J.*, *56*, 295 (1922).

Absorption of cupric chloride solution: Coblentz, W. W., *Bureau of Standards Scientific Paper No. 168.*



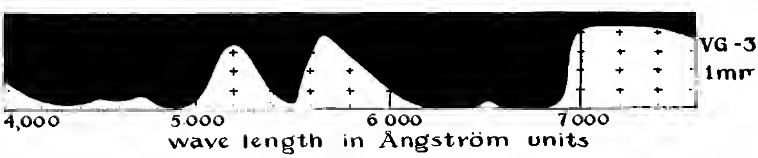


Fig. 25. Transmission of glass and Wratten filters.

spectrum.[45] (See Table X and also *Jena Colored Optical Filter Glasses,* obtainable from Fish-Schurman Corporation, 250 East 43rd Street, New York City.) The transmission of

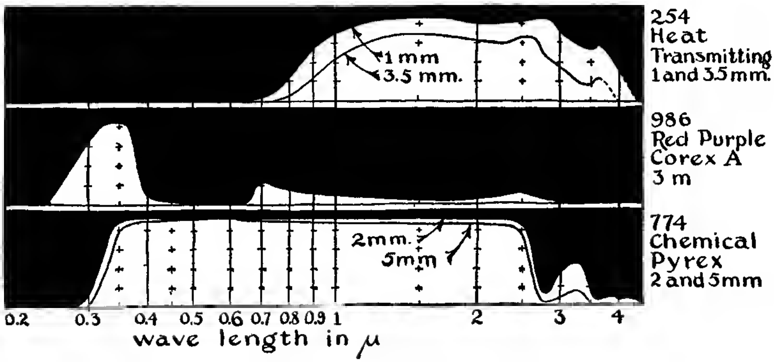


Fig. 26. From *Glass Color Filters,* Corning Glass Works, Corning, New York.

BG17, 1 mm thick, and BG19, 4 mm thick, is about the same as that of 2 cm of a nearly saturated copper sulphate solution.

Visible spectrum. Glass and gelatin filters are used for isolation of the mercury lines. They are easier to handle and much more permanent than water solutions. The transmissions of some of the glass and gelatin filters commercially available in this country are illustrated in Figs. 25 and 26. A list of the filter combinations for the separation of various spectrum lines is given in Table XI.

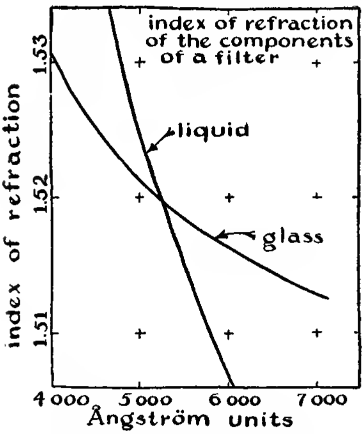


Fig. 27. After McAlister. (See footnote 46.)

The Christiansen filter. The Christiansen filter consists of a mass of solid particles immersed in a liquid medium, as,

[45] Heat-absorbing glass is manufactured by the Corning Glass Company, Corning, New York. BG17 and BG19, manufactured by Schott und Gen., are handled in this country by the Fish-Schurman Company, New York City.

for example, particles of borosilicate glass immersed in carbon disulphide and benzene.[46] Fig. 27 shows the dispersion for a borosilicate crown glass and for a 10 per cent solution (by

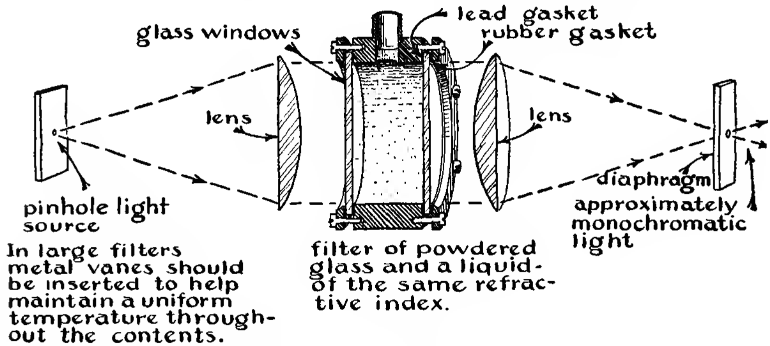


Fig. 28. After McAlister.[46]

volume) of carbon disulphide in benzene (both anhydrous) at 20°C. The filter composed of these two transmits freely the color for which the indices of refraction of the liquid and solid phases are identical, that is, where the two lines in Fig. 27 cross. For this color the medium is optically homogeneous. The filter is a nonhomogeneous optical medium for all other wave lengths. Accordingly, they are scattered. By means of the arrangement shown in Fig. 28, the scattered waves are isolated from the freely transmitted color. The individual transmissions of five filters are shown in Fig. 29. These filters were 18 mm thick and were made up from borosilicate glass using different concentrations of carbon disulphide in benzene.

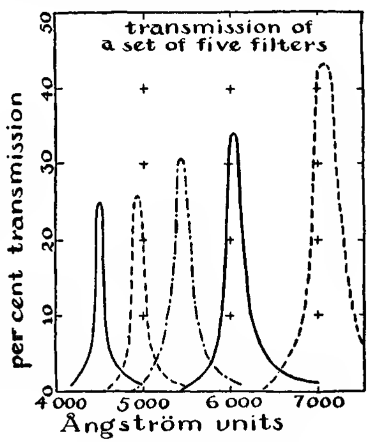


Fig. 29. After McAlister.[46]

[46] Christiansen, C., *Ann. Physik u. Chemie*, *23*, 298 (1884), *24*, 439 (1885). McAlister, E. D., *Smithsonian Misc. Coll.*, *93*, No. 7 (1935).

One limitation of the Christiansen filter lies in its lack of complete opacity to wave lengths on either side of the transmitted band.

TABLE XI

FILTERS FOR ISOLATING MERCURY LINES

Radiation	Corning Glass	Eastman Wratten	Liquid Filters
Infrared or 10,140	G554EK, 6 to 8mm	88 as used by R. W. Wood or 89A	Cobalt blue glass and saturated solution of potassium dichromate
5769 to 5790	G34R, 3 to 4 mm	22 Hg yellow	Chrysoidine and eosin
5461	G555Q, 8 to 10 mm, and G34Y, 3 to 4 mm	62 Hg green or 77 Hg special or 77 A. Hg special for interferometry	Neodymium ammonium nitrate and potassium dichromate
4359	Noviol A, 3 mm, and G585, 3 to 5 mm	50 Hg blue	Cobalt blue glass and quinine sulphate
4047 to 4078	G586A, 3 to 5 mm, and Noviol 0, 3 to 4 mm	36 Hg violet	Methyl violet and quinine sulphate
3650 3656 3663	G586AW, 8 to 10 mm	18 ultraviolet	Methyl violet and acid green

Buttolph, L. J., *Engineering Bulletin 104-B*, Cooper-Hewitt Company.

This limitation is a serious one. For example, when the filter is to be used in conjunction with a highly selective receiver, such as a photocell, the response of the receiver for rays weakly transmitted by the filter but for which the receiver is exceptionally sensitive (or for which the emission of the source is especially strong) may seriously interfere with the interpretation of the results obtained. Another limitation of this filter is its sensitivity to temperature changes. Because of this, the filter cannot be used effectively in an intense beam of light such as sunlight, owing to temperature gradients set up in the cell.

However, the dependence of the transmitted wave length upon temperature may be put to use. F. Weigert and

collaborators have found, for example, that a cell made of particles of crown glass immersed in liquid methyl benzoate transmitted red light at 18°C. (64°F.) and blue light at 50°C. (122°F.).[47]

A very interesting Christiansen filter effect is exhibited by the infrared transmission of thin powder films.[48] Their maximum of transmission occurs at the wave length at which the index of the powder is unity or equal to the index of the surrounding medium. For magnesia this transmission maximum in air is at 12.2μ, and if the filter is immersed in carbon tetrachloride, the maximum shifts to wave length 9μ, at which both the carbon tetrachloride and the magnesia have the same index.

Reflection of metals. Of the metals useful in the visible spectrum for reflection of light, the three most important are aluminum, speculum, and silver. Their reflectivities are shown in Fig. 30. It is to be noted that aluminum is

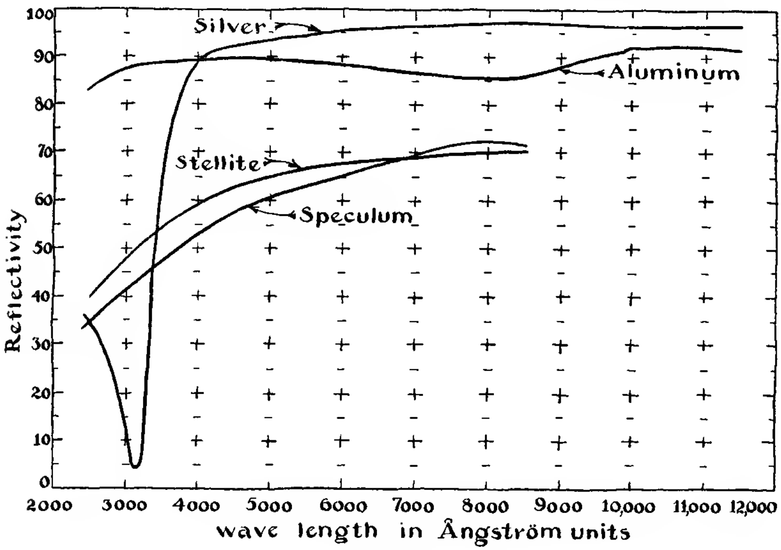


Fig. 30.

[47] Weigert, F., Staude, H., Elvegard, E., and Shidei, J., *Zeits. f. phys. Chem., Abt. B*, *2*, 149 (1923), *9*, 329 (1930).
[48] Barnes, R. B., and Bonner, L. G., *Phys. Rev.*, *49*, 732 (1936).

superior to newly deposited silver for all wave lengths less than 4100 Å. In the visible spectrum the use of aluminum instead of silver is recommended. Although new silver has a better reflectivity in the visible spectrum than aluminum, it soon tarnishes.

The apparatus shown in Fig. 31 was used for the above reflectivity measurements. This apparatus measures the

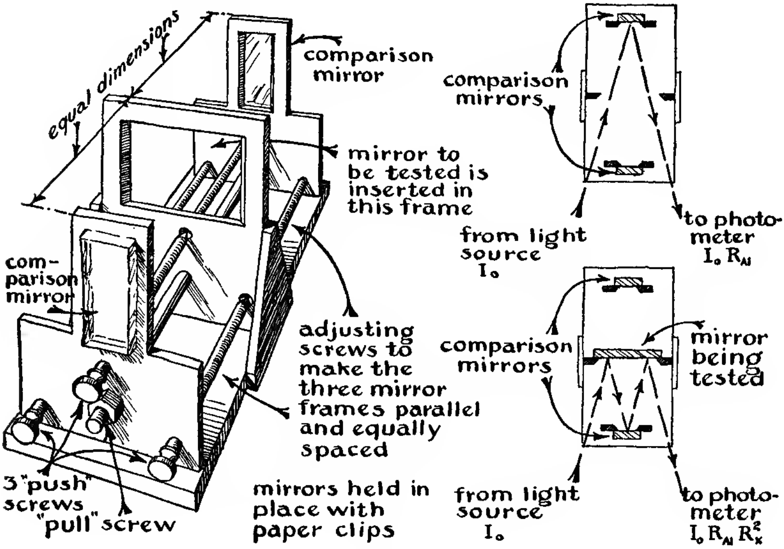


Fig. 31.

square of the absolute reflectivity directly (putting the comparison mirror in both the numerator and denominator, so to speak).

Monochromators. The best method of isolating a narrow wave-length band of high spectral purity from a source of white light is to use a double monochromator, that is, two single monochromators built together. High spectral purity is often desirable for highly selective effects, such as, for example, the determination of the long wave-length limit of the photoelectric effect, or in any other case when the slight spectral impurity that one might have with a single monochromator would vitiate the results of the measurement. A

step can be made in the direction of high spectral purity by the use of filters in series with a single monochromator. These filters are, however, usually less efficient than a single monochromator. The transmission of a single monochromator is about 45 per cent.

The monochromator may have achromatic lenses, but these are very expensive if they are constructed of materials

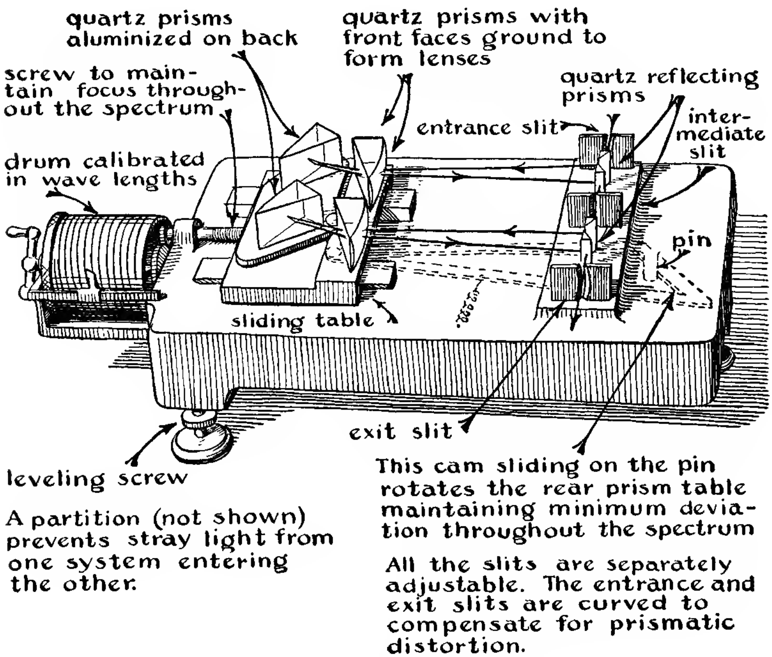


Fig. 32. Hilger-Müller double monochromator.

which will function in the ultraviolet. Generally, monochromators employ quartz lenses. These are brought to focus with a mechanism operated by the wave-length drum. Fig. 32 shows how this is accomplished in the Hilger-Müller double monochromator by the use of a cam bar mounted on the prism table. As the prism table and lens system move as a unit toward the slit system, the lenses are brought into focus for shorter and shorter wave lengths. The cam bar is

so constructed that it causes the wave lengths to fall on the exit slits for which the lenses are in focus.

Use of mirrors in monochromators. Parabolic mirrors are often used in monochromators, because an optical system using mirrors is achromatic. However, mirrors have the distinct disadvantage as compared with lenses that the parallel collimated beam is returned in the direction of the entrance slit, a direction which precludes a neat simple arrangement of the other optical parts. To use a mirror on

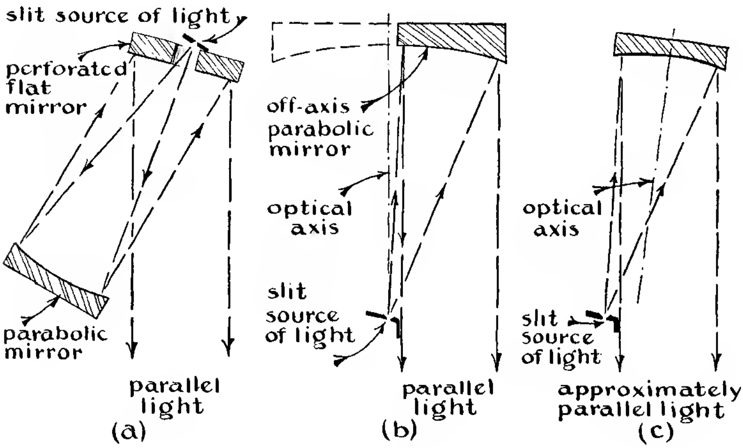


Fig. 33.

its optical axis requires either an auxiliary flat as in the Pfund[49] arrangement shown in Fig. 33(a) or an off-axis mirror as shown in Fig. 33(b). One way to make such an off-axis mirror is to construct a large ordinary paraboloidal mirror and cut out the desired mirror from one side of it.

A mirror system composed of spherical mirrors like the one shown in Fig. 33(c) may be used. This, of course, introduces large distortions in the wave front. It is possible, however, by proper orientation of a similarly imperfect

Pfund, A. H., *J. O. S. A.*, *14*, 337 (1927). For a grating spectrometer application of Pfund's scheme see Randall, H. M., *Rev. Sci. Instruments*, *3*, 196 (1932).

Hardy, J. D., *Phys. Rev.*, *38*, 2162 (1931).

mirror to compensate in a measure for the distortions produced by the collimator and to obtain better definition than would be possible even if a perfect telescope were used. The proper arrangement of the telescope system for achieving this compensation is shown in Fig. 34, with the regular Wadsworth arrangement.[50]

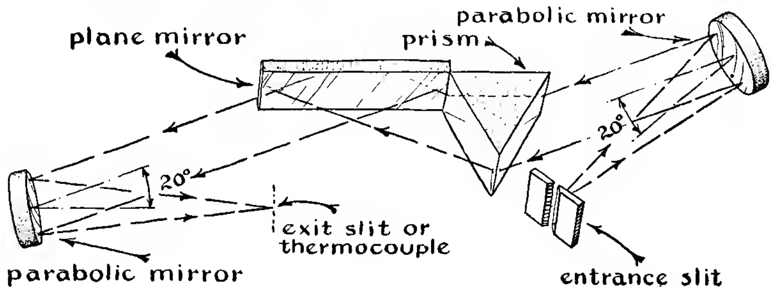


Fig. 34.

The optical train in monochromators is usually either the Littrow arrangement or the Wadsworth arrangement, both of which use the prism at minimum deviation. These arrangements are shown in Fig. 35.[51]

Water monochromator. An ultraviolet monochromator with improvised optics, devised by Harrison,[52] is shown in Fig. 36. The optical parts consist of a water prism and a spherical aluminized mirror. This monochromator is very simple, and optically it is good enough for isolating the stronger mercury lines (as the illustration of the produced spectrum shows). It has a relatively high aperture, $f/6$. The dispersions of crystal quartz, fused quartz, and water are related as 25:21:19 at 3000 Å. Since water is more transparent to the ultraviolet than quartz, this monochromator can be used for isolating wave lengths as short as 1820 Å.

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[50] Czerny, M., and Turner, A. F., *Zeits. f. Physik, 61*, 792 (1930).
Czerny, M., and Plettig, V., *Zeits. f. Physik, 63*, 590 (1930).

[51] Littrow, O., *Am. J. Sci., 35*, 413 (1862).
Wadsworth, F. L. O., *Phil. Mag., 38*, 137 (1894); *Astrophys. J., 2*, 264 (1895).

[52] Harrison, George R., *Rev. Sci. Instruments, 5*, 149 (1934).

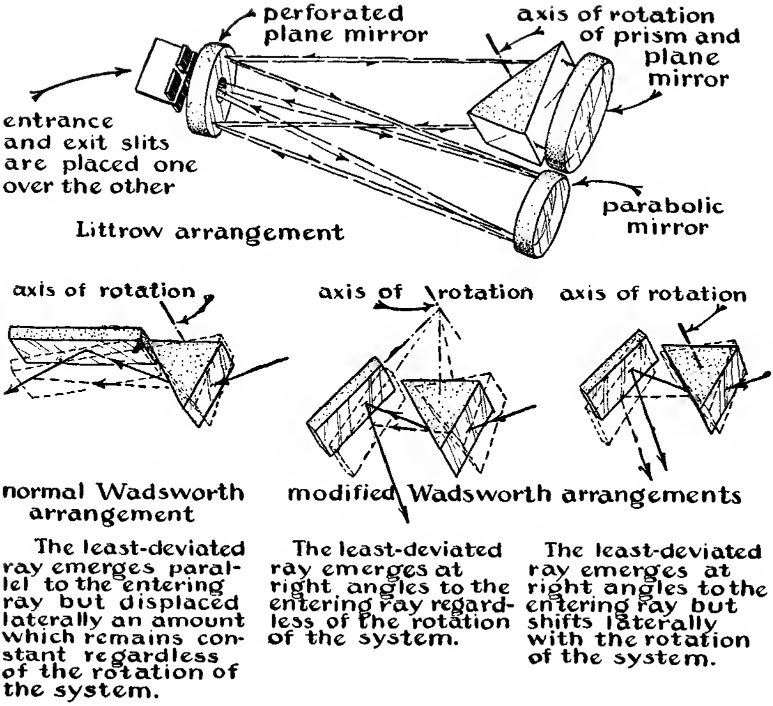
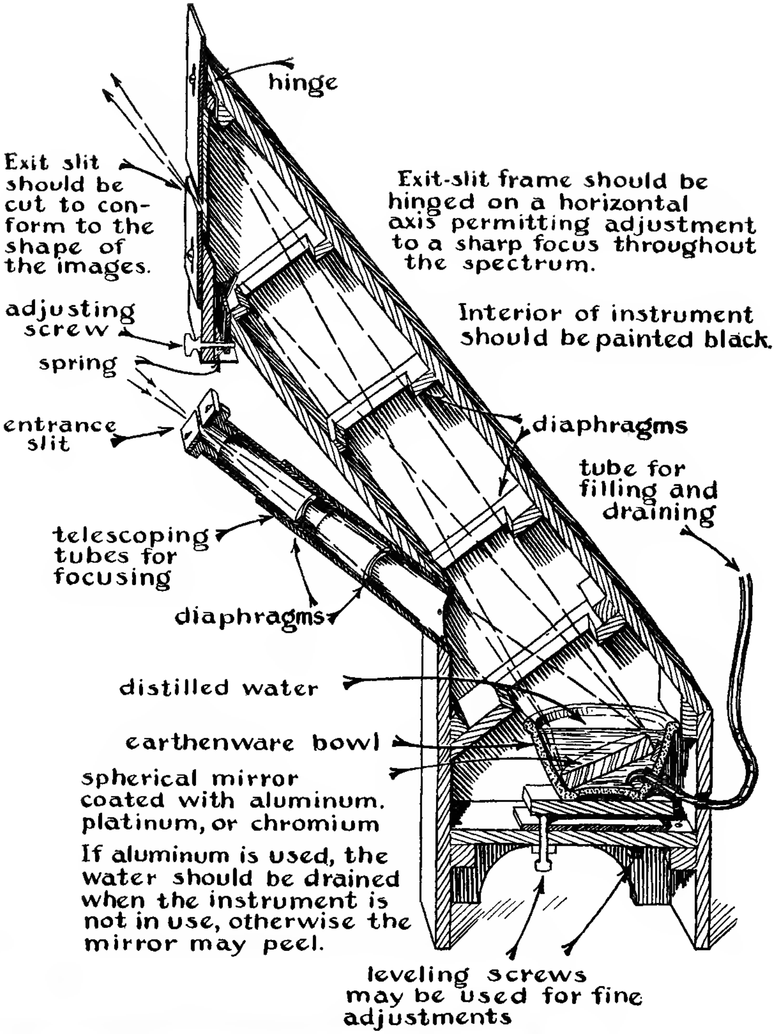


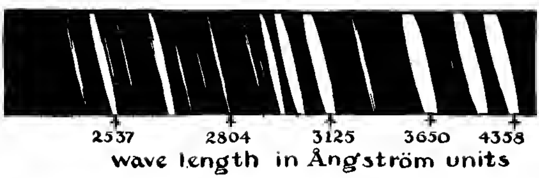
Fig. 35.

Focal isolation. Fig. 37 shows the method of focal isolation invented by Wood to isolate the far infrared radiations from a Welsbach burner.[53] When the first lens is positioned in relation to the light source at a distance equal to twice its focal length for the far infrared rays, where the index of refraction is 2.25, the near infrared rays emerging from the lens are divergent. An opaque spot at the center of the quartz lens prevents the direct transmission of the median near infrared rays through the aperture provided at the focus of the far infrared rays. Usually two lenses are arranged in series of effect complete separation of the far infrared rays.

A focal isolation method has been applied to the isolation

[49] Rubens, H., and Wood, R. W., *Phil. Mag.*, *21*, 249 (1911).





A drawing from a photograph of part of the mercury-arc spectrum taken with an instrument similar to that above, but using an oblique slit.

Fig. 36.

of the 1940 Å group of aluminum lines with a quartz lens.[54] And, while there is for quartz no such diversity of index in this part of the spectrum as there is in the infrared, yet these lines are separated from the rest of the aluminum spectrum with a spectral purity of 0.98. The intensity obtained is sevenfold greater than that obtainable from a quartz monochromator. This focal isolation method has also been applied to the 2030 Å to 2140 Å group of zinc lines.

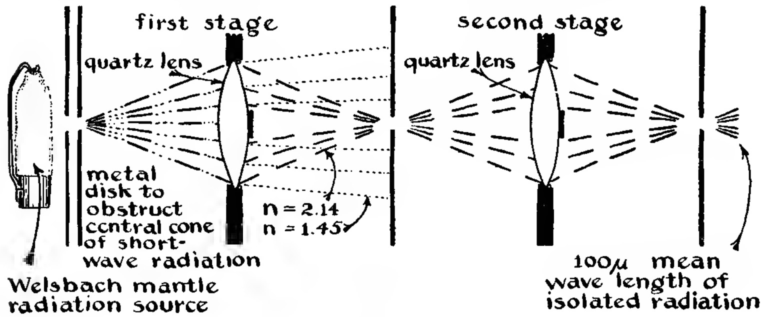


Fig. 37.

Residual-ray isolation. Apparatus using the residual-ray method for the isolation of wave lengths in the infrared is illustrated in Fig 38.[55] The apparatus shown at the top of this figure employs four crystal reflections, while the one at the bottom, placed at the focus of an image-forming mirror, uses only two crystal reflections.

When the two-crystal apparatus is equipped for 6.7μ (crystals of calcite) it is useful for measuring humidity, since this region of the spectrum is very sensitive to moisture in the radiation path. On the other hand, with either quartz, Carborundum, or potassium chromate crystals, which give bands of radiation at 8.7μ, 12μ, and 11.6μ, respectively, the instrument is useful as a radiation pyrometer insensitive both to water vapor and to light smoke or haze. In the region from 8μ to 13μ there is very little absorption by the

[54] Forbes, Geo. S., Heidt, Lawrence J., and Spooner, Lawrence W., *Rev. Sci. Instruments*, *5*, 253 (1934).

[55] Strong, J., *Phys. Rev.*, *37*, 1565 (1931), *38*, 1818 (1931).

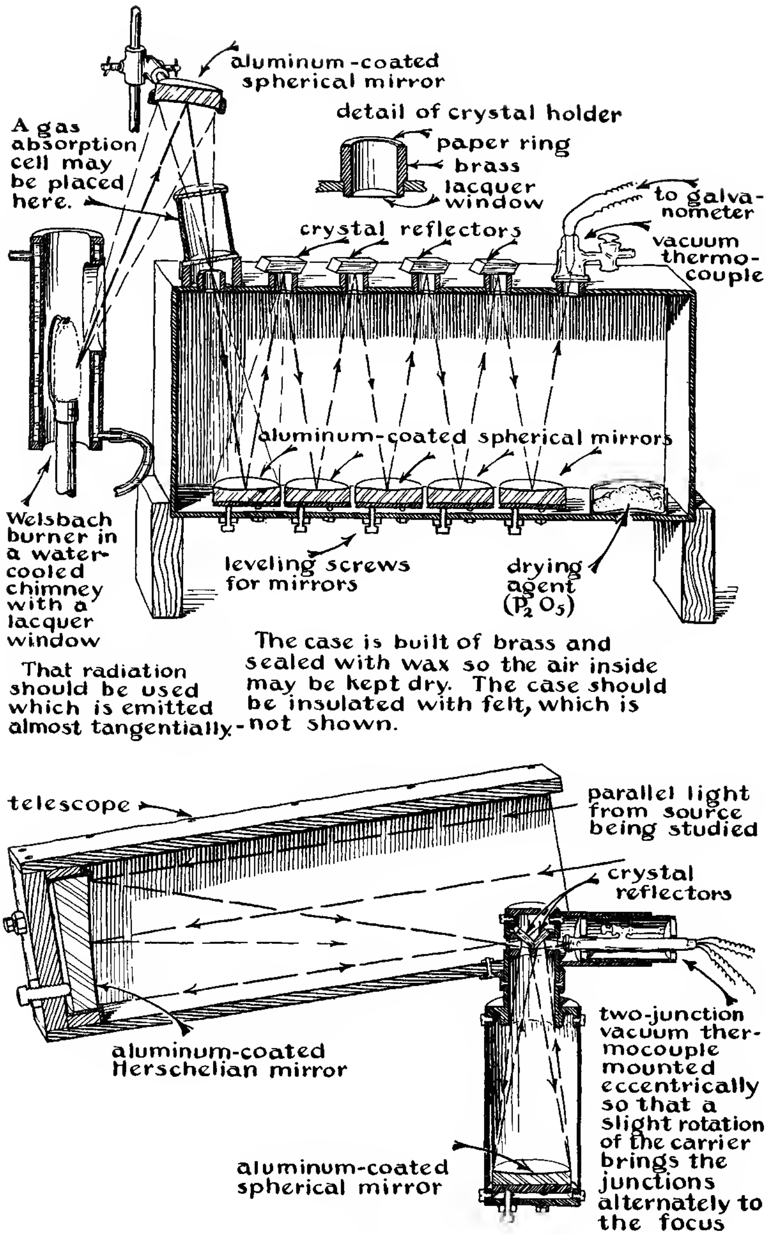

aluminum-coated spherical mirror
detail of crystal holder
paper ring
brass
lacquer window
A gas absorption cell may be placed here.
crystal reflectors
to galvanometer
vacuum thermocouple
aluminum-coated spherical mirrors
Welsbach burner in a water-cooled chimney with a lacquer window
leveling screws for mirrors
drying agent (P_2O_5)
The case is built of brass and sealed with wax so the air inside may be kept dry. The case should be insulated with felt, which is not shown.
That radiation should be used which is emitted almost tangentially.
telescope
parallel light from source being studied
crystal reflectors
two-junction vacuum thermocouple mounted eccentrically so that a slight rotation of the carrier brings the junctions alternately to the focus
aluminum-coated Herschelian mirror
aluminum-coated spherical mirror

Fig. 38.

water in the air even when it is humid; in this region of the spectrum the entire thickness of the atmosphere exhibits a transmission comparable to the transmission of the atmosphere for green and yellow light (T = 85 per cent).

Polarization. There are now new polarizers available for use in the visible spectrum, but they are not as efficient as Nicol prisms.[56] The transmission of these polarizers, shown in Fig. 39, does not yield as high efficiency as that of a Nicol prism. For plane-polarized light of proper azimuth a Nicol prism transmits about 80 per cent. Two Nicol prisms in

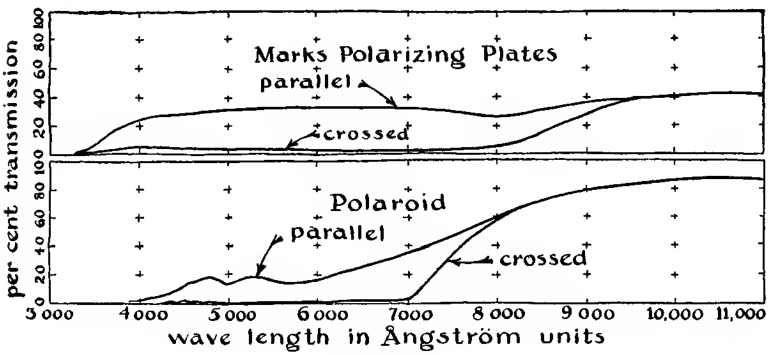


Fig. 39.

series transmit a maximum of about 32 per cent of unpolarized white light. At the other extreme, two Nicol prisms accurately crossed are quite opaque. For example, they will not transmit enough sunlight to make the disk of the sun discernible. However, to obtain this degree of opacity, the Nicol prisms must be crossed very precisely (to an accuracy of the order of 1 second of arc).

The new polarizers have the advantage over Nicol prisms that they can polarize a beam of greater aperture (both areal and angular). Two applications of the new polarizers are illustrated in Figs. 40 and 41.

One of these, illustrated in Fig. 40, applies to the measurement of strain in glass. Objects to be tested for strain, as,

[56] Strong, J., *J. O. S. A.*, *26*, 256 (1936).

for example, glass-to-metal seals, are immersed in a jar fitted with parallel glass sides and containing a liquid medium having the same index of refraction as the glass. This medium may, for example, be a mixture of the proper proportions of carbon disulphide and benzene or a mixture of zylene and alcohol. Polarized light obtained from a lamp by reflection off black glass at the polarizing angle (or reflection off the back of an exposed photographic plate which has been developed, fixed, and dried) is viewed through a full-wave

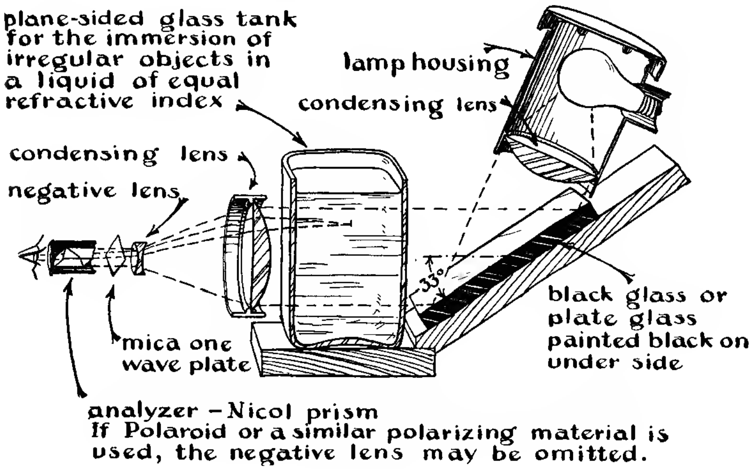


Fig. 40.

mica plate and analyzer. (The construction of the full-wave plate is described below.) When a full-wave plate is placed in front of the analyzer, slight variations of the polarization over the field of view are manifest as variations of color from the purple of the unstressed condition.

Engineering applications of polarized light. The property of isotropic transparent materials that a strain makes them double refracting is used by engineers for studying the magnitude and distribution of stress produced by loading various two-dimensional structures, such as, for example, the shapes represented by the cross section of a dam.[57] An arrange-

[57] Brahtz, J. H. A., *Rev. Sci. Instruments*, *5*, 80 (1934).
Goetz, A., *Rev. Sci. Instruments*, *5*, 84 (1934).

ment for such studies using spherical mirrors and the new polarizers is shown in Fig. 41. The astigmatism (due to using the mirrors off axis) can be balanced out, at least in part, by tipping the camera lens about a horizontal axis by a suitable amount. The model of the shape to be tested is usually made from a clear sheet of Bakelite or Marblette. Table XII gives the coefficient of forced double refraction for various materials suitable for constructing models.

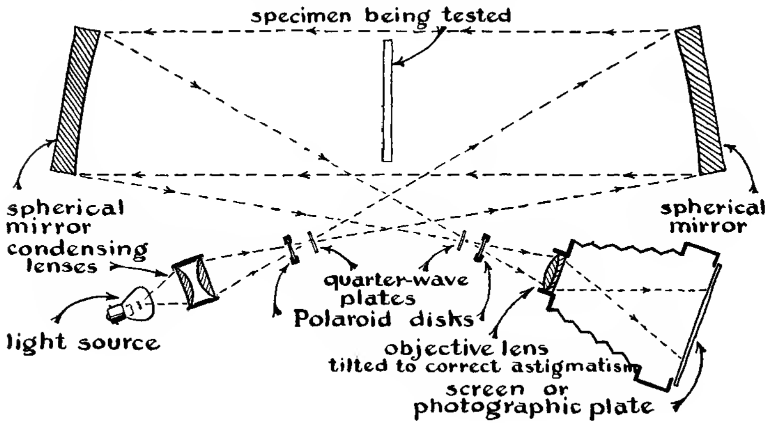


Fig. 41.

The quarter-wave plates are used in the illustrated arrangement to allow the elimination of the pattern of isoclinics (the lines along which the principal stress in the specimen has a constant inclination) from the pattern of isochromatics (the lines along which the quantity $(p - q)$ has a constant value). Here p and q are the principal stresses produced in the model by the applied loading. Methods of determining the magnitude of the quantities p and q from the measured isoclinics and isochromatics cannot be described here, since they are quite complicated.[58]

[58] Coker, E. G., and Filon, L. N. G., *A Treatise on Photo-Elasticity.* London: Cambridge University Press, 1931; New York: The Macmillan Company, 1932.

Horger, O. J., *Jour. of Applied Physics*, *9*, 457 (1938). This article contains a good bibliography on the subject.

However, in spite of this, the experimental method of studying the stresses in many structures is easier than the theoretical method, and the experimental method has the advantage over the theoretical method that it carries with it the conviction of a more direct appeal to nature for the information desired.

Quarter-, half-, and full-wave plates. Quarter-, half-, and full-wave plates are made of quartz, selenite, or mica cut or split parallel to the optical axis. The thickness of the plate is made such that the relative retardation of the ordinary and extraordinary ray is $\frac{1}{4}$, $\frac{1}{2}$, or 1 full wave length. The thickness τ required for a quarter-wave plate is

$$\tau = \frac{\lambda}{4(n_e - n_o)}, \tag{2}$$

where n_e is the index of the crystal for the extraordinary ray and n_o for the ordinary, and λ is the wave length in question. For mica the thickness of a quarter-wave plate for the D

TABLE XII

Material	Elastic Limit (lbs./square inch)	Coefficient of Forced Double Refraction (Brewster's)
Glass	....	2.7
Celluloid	4000	11.1
Bakelite	5500	44.5
Phenolite	7000	56.7
Marblette	2750	132.5

Carleton, R. B., *Rev. Sci. Instruments*, *5*, 30 (1934).
Solakian, Arshag G., *Mech. Eng.*, December, page 767 (1935).

lines is about 0.036 mm. Although for mica the quantity $(n_e - n_o)$ varies from specimen to specimen,[59] it can be taken as essentially constant for all wave lengths. Therefore, the thickness of a quarter-wave plate is roughly proportional to the wave length for which it is intended.

[59] Einsporn, E., *Phys. Zeits.*, *37*, 83 (1936).

A quarter-wave plate, when it is set perpendicular to a beam of polarized light with its principal directions at 45° to the azimuth of polarization, retards one half of the polarized light until its phase is 90° behind the phase of the other half, thus producing circular polarized light. Conversely, a quarter-wave plate will change circular to plane-polarized light. A half-wave plate, similarly oriented, transforms plane-polarized light to plane-polarized light rotated in azimuth by 90°.

The principal directions of mica are determined by interposing it between crossed Nicols. The principal directions are parallel and at right angles to the azimuth of polarization of the incident light when the mica (of any thickness) is so oriented that it does not affect the cutoff of the second Nicol.

Tutton's test[60] for distinguishing between the two principal directions in a quarter-wave plate is to place the plate between crossed Nicols (with its plane perpendicular to the axis of the beam of incident white polarized light) oriented in an azimuth such that the restored light is a maximum. The principal directions in the plate now make angles of 45° with the azimuth of vibration of the incident polarized light. The mica plate is rotated first about one principal direction and then about the other, so that, in each case, light traverses a thicker layer of mica. In one case the color passes from bluish gray through iron gray to black, and in the other case the color passes from white to yellow and then through colors of a higher order. The latter color sequence corresponds to rotation about the principal direction of slower vibration in the mica and the first case corresponds to the principal direction of faster vibration in the mica.

Splitting of mica. Quarter-wave plates are most easily made from mica, since it is easily split to the thickness required.

The stock sheets are split from clear mica plates.[61] The

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[60] Kaplan, Joseph, *J. O. S. A.*, *14*, 186 (1927).

[61] Mica is obtainable from Eugene Munsell, 200 Varick Street, New York City.

starting sheet is trimmed to about 3 inches square with sharp tin snips so as to have clean edges. (The exact size of the starting sheet is immaterial.) One corner of the starting sheet is then frayed out by rubbing it, and a clean dissecting needle is introduced to divide the sheet approximately in half. A drop of water is introduced in the cavity so produced.[62] The mica is then split all around the edges by working the needle along, point first, at an angle of about 30°, so that the first cleavage starts inside the boundary of the sheet. This avoids a terraced cleavage. After the needle has gone around the circumference, a second drop of water is introduced, and the plates are drawn apart. The water so facilitates cleavage that the sheets may be separated almost as easily as the pages of a book. This process is repeated until the thickness is approximately 0.036 mm or as thin as desired. Each time, the sheet is divided so as to give two sheets of approximately the same thickness.

Mica gauges.[63] A gauge may be made up as shown in Fig. 42. To make such a gauge the principal directions are

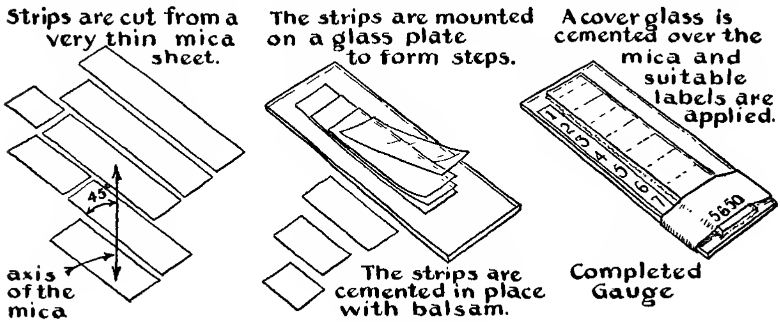

Fig. 42.

first marked on a starting plate. The thinnest possible sheet is then split from the starting plate and cut up into strips about $\frac{1}{4}$ inch wide. The strips are cut at an angle of 45° with the principal directions. These strips are then cut to

[62] Strong, J., *Rev. Sci. Instruments*, *6*, 243 (1935).

[63] Wright, Lewis, *Light*, page 289. New York: The Macmillan Company, 1892.

give rectangles with lengths of 2 inches, $1\frac{7}{8}$ inches, $1\frac{3}{4}$ inches, $1\frac{5}{8}$ inches, and so forth. (See Fig. 42.) The strips are next cemented (with balsam) between glass plates as illustrated, care being exercised to see that none of the strips are mounted upside down or rotated end for end. The steps so formed are then indexed.

The retardation per step of the gauge is determined as follows: After the analyzer is set for maximum transmission of the light, the gauge is placed on the mirror of the Norremberg doubler (see Fig. 43) either parallel or perpendicular to the azimuth of polarization. A sodium light should be used for illumination. The index number of the step which gives opacity is noted. The step giving opacity is a quarter-wave plate for the D lines. Other steps are proportionately greater and less.

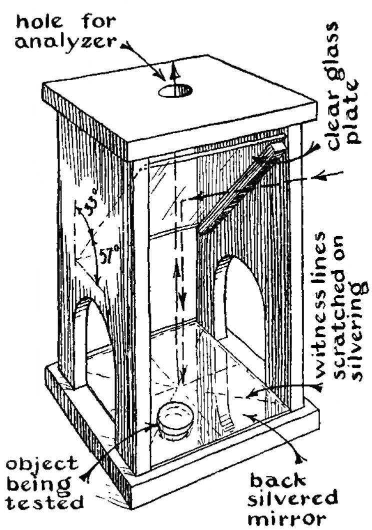

Fig. 43.

Using the gauge. The gauge is used as follows: First, the analyzing Nicol of the Norremberg doubler is set for extinction. The mica of unknown thickness is placed on the bottom mirror of the doubler, with its principal direction making an angle of 45° with the azimuth of polarization to give maximum transmission. Then the gauge strip is laid on top of the mica so that it is either parallel or perpendicular to the azimuth of polarization. At one of these orientations, the steps show "interference" colors, and at the other, and proper one, opacity is obtained for one or two of the steps. The calibration value of the step which gives opacity corresponds to the retardation of the mica sample. Interpolation may be required to make a delicate measurement.

Magnification of lenses. The transverse magnification of a lens is the ratio of image diameter to object diameter, or, expressed another way, it is the ratio of transverse image displacement to transverse object displacement. For a simple lens the magnification is given by the ratio of image distance to object distance. For a system such as a spectrometer, which has a collimating element (lens or mirror) with the object at or near its focal plane and a telescope element also with the image at or near its focal plane, the magnification produced is the ratio of the focal length of the telescope element to that of the collimating element.

Another case, encountered in a telescope, is that in which parallel light is received by the objective and observed by an eyepiece adjusted so that its focal plane is very near the focus of the objective. Here, the angular magnifying power is the ratio of the focal length of the objective to that of the eyepiece.

The longitudinal magnification of an image-forming system gives the ratio of the displacement of the image along the optical axis to the displacement of the object. In the case of a system composed of two lenses (or mirrors) with the object and image at or near the respective focal planes of these elements, the longitudinal magnification is given by the square of the ratio of the focal lengths.

Other properties of lenses. When a beam of parallel light is focused with a thin lens on the optical axis, its focal length f is given by the expression

$$\frac{1}{f} = \left(\frac{1}{r_1} + \frac{1}{r_2}\right)(n - 1), \tag{3}$$

where r_1 and r_2 are the respective radii of curvature of the two surfaces of the lens, and n is the index of refraction of the material from which the lens is constructed. The r's are taken positive if the curvature acts to converge the light.

If the light is inclined to the optical axis of the lens, it exhibits astigmatism as shown in Fig. 44. For example, the best focus of a distant star, which would be a small hard spot

of light on the optical axis, is a soft image when the lens is inclined. The diameter of the smallest image is known as the "circle of least confusion." Within the focal distance giving the smallest off-axis image, the lens gives at one particular distance a rather sharp line focus, which is perpendicular to the plane passing through the image and the optical axis. Also, outside this image another rather sharp line focus is obtained. This line focus is perpendicular to the first line and parallel to the plane referred to above.

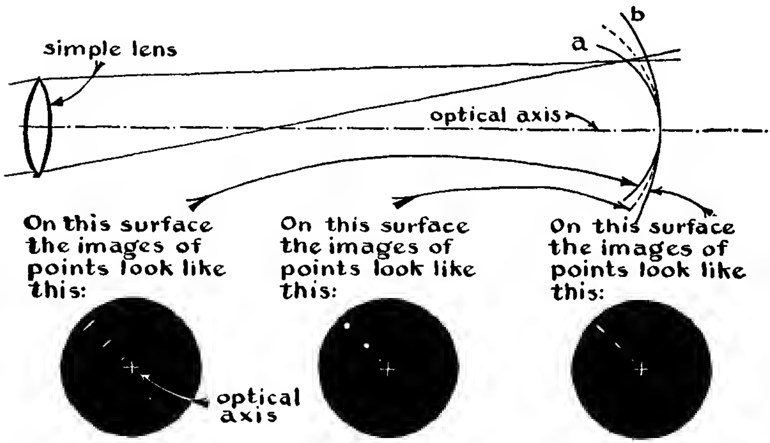

Fig. 44.

The astigmatism of a simple lens is illustrated in Fig. 44. The locus of the inner astigmatic images is a circle, a, having a diameter

$$d = \frac{f}{3 + n^{-1}}, \tag{4}$$

or $0.275\,f$ for $n = 1.5$, and the locus of the outer astigmatic images is a circle, b, of diameter

$$d = \frac{f}{1 + n^{-1}}, \tag{5}$$

or $0.6\,f$ for $n = 1.5$.

Properties of mirrors. The mirrors generally used in optics are conic sections of revolution and the flat. They are paraboloidal for focusing parallel light, ellipsoidal for two

conjugate real focii, and hyperboloidal for two conjugate focii, one of which is virtual. The spherical mirror is, of course, suited for focusing light from a source at its center of curvature exactly back on the center.

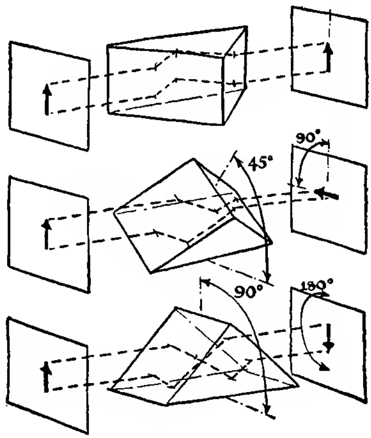

Fig. 45.

When a spherical mirror of radius R is used to focus parallel light striking it at an angle, the image exhibits astigmatism, and the lines corresponding to the two circles shown in Fig. 44, determined by the positions of the astigmatic images, are a circle of diameter R and a straight line, respectively. (See Fig. 21, Chapter XI.)

Properties of prisms. Some interesting properties of a right-angle prism are illustrated in Fig. 45.

This prism, viewed through the long face and perpendicular to the vertex of the 90° dihedral angle in one azimuth, has the interesting and often useful property of returning a beam of light back on its path, regardless of the angle of incidence on the long face in the other azimuth. Fig. 46 illustrates the corresponding property for the corner of a cube.

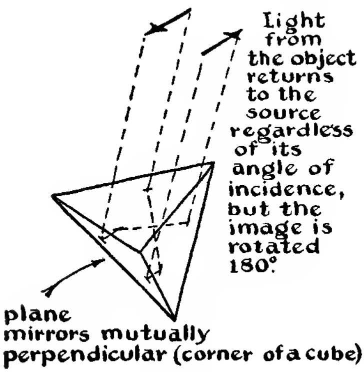

Fig. 46.

Optical recording systems. Professor Hardy has written an excellent article on recording systems as applied to oscillographs.[64] We can refer only to his results. He concludes

[64] Hardy, A. C., *J. O. S. A.*, *14*, 505 (1927).

that a simple optical system with a single lens in front of the galvanometer mirror will give as much illumination on the recording film, on a basis of equal resolving power, as any other possible stigmatic system. Furthermore, he points out that the focal length of the simple systems should be chosen so that the limit to the resolving power is set by the photographic material rather than by interference effects. Although 25 lines/mm or more can be resolved by photography, Hardy sets an arbitrary practical limit of 0.1 mm as the resolving power of the photographic material. To obtain maximum illumination and at the same time to conserve on the use of photographic materials, the simple lens should be chosen to give a spot at least 0.1 mm wide.

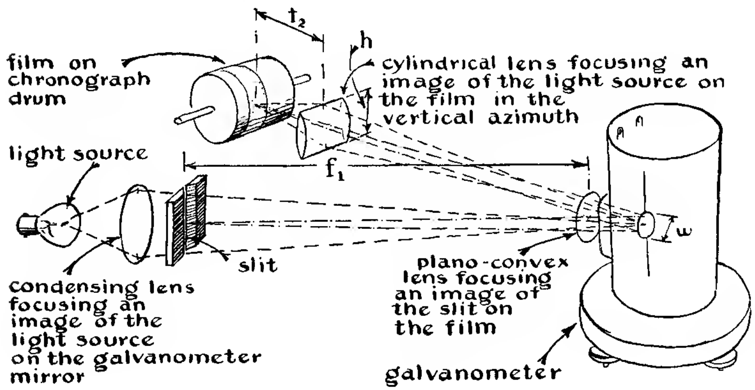

Fig. 47.

However, by using an astigmatic optical system such as the one shown in Fig. 47, it is easily possible to obtain nine times as much illumination as with the simple lens. Furthermore, the astigmatic system has the additional advantage that rotation of the galvanometer mirror about a horizontal axis does not produce a vertical deflection of the image on the recording film.

The calculation of the maximum velocity at which the recording spot can traverse the photographic emulsion and still yield a perceptible trace is treated in Chapter XI.

This treatment includes the astigmatic case illustrated in Fig. 47. Owing to the recent developments in fast photographic emulsions, the data given in Table VI, Chapter XI, for the various materials may be regarded as being distinctly conservative.

A bibliography of some of the best works on the subjects treated in this chapter is given in a footnote.[65]

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[65] Baly, E. C. C., *Spectroscopy.* New York: Longmans, Green and Company, 1927.

Forsythe, W. E., *Measurement of Radiant Energy.* New York: McGraw-Hill Book Company, 1937.

Hardy, A. C., and Perrin, F. H., *The Principles of Optics.* New York: McGraw-Hill Book Company, 1932.

Lecomte, J., *La Spectre Infrarouge.* Les Presses Universitaires de France, 1928.

Meyer, Charles F., *The Diffraction of Light, X-rays and Material Particles.* Chicago: University of Chicago Press, 1934.

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Wood, R. W., *Physical Optics*, Third Edition. New York: The Macmillan Company, 1934.

CHAPTER X

Photoelectric Cells and Amplifiers

BY

A. E. WHITFORD

Introduction

THE photoelectric cell has found an important place in the physical laboratory as a device for the measurement of the intensity of radiation, and as such may be classed with the thermocouple and the photographic plate. In common with the photographic plate its response varies with wave length, so that it does not measure energy directly, as does the thermocouple. The photographic plate, because of its ability to integrate extremely long exposures, can be used to measure smaller quantities of radiation than can the photoelectric cell. But the photographic plate has the definite disadvantage that its blackening is a complicated function of intensity and exposure time, necessitating a series of calibration exposures whose intensity ratios are known. Furthermore, plate grain, local variations in emulsion sensitivity, and nonuniform development place limitations on the precision obtainable in photographic photometry. Both the photocell and the thermocouple, when used with suitable precautions, give a response linear with respect to the intensity, and both are capable of giving more precise results than the photographic plate. In the infrared beyond about 10,000 Å, the thermocouple (or other heat-sensitive devices such as the bolometer) must be used. At shorter wave lengths, however, it is possible to measure much smaller amounts of radiation with the photoelectric cell than with the thermocouple.

Limit of detection compared. An attempt to set an ultimate limit for any of the above-mentioned detectors of radiation must of necessity be approximate, because the working limit depends on various factors such as the angular size and shape of the source, the spectral distribution of the radiation it gives out, and the presence or absence of background radiation. Because the stars offer a common basis for comparing the response of light-sensitive devices to weak sources, they are chosen as reference standards in this discussion. The magnitudes of the stars form a logarithmic scale such that an intensity ratio of 100 times corresponds to 5 magnitudes. Thus 1 magnitude represents an intensity ratio of $\sqrt[5]{100}$, or 2.512. . . . In general, the difference in magnitude between two stars whose intensities are I_1 and I_2 is given by $m_1 - m_2 = 2.5 \log_{10} I_2/I_1$. A candle at a kilometer has been found[1] equivalent to a star of visual magnitude $+ 0.8$, approximately the brightness of Altair. From these relations one may easily derive an equation giving the amount of light received by a telescope from a given star. If m is the visual magnitude of the star, d the diameter of the telescope in inches, and Q the amount of light expressed in lumens,[2] then it may be shown that

$$2.5 \log_{10} Q = 7.57 - 30 + 5 \log_{10} d - m.$$

As an example, we may compute the amount of light received by a 1-inch telescope from the polestar,[3] which has a visual magnitude of 2.1. Substitution in the formula gives 1.5×10^{-10} lumen. Of course, the stars differ among themselves as to the spectral distribution of the light they give out. In this comparison, stars of spectral class G_0 having

[1] Russell, H. N., *Astrophys. J.*, *43*, 129 (1916).

[2] The lumen is the unit of luminous flux. It is equal to the flux emitted in a unit solid angle by a uniform point source of 1 international candle.

[3] Polaris, in combination with a small laboratory telescope, provides a convenient order-of-magnitude standard source for testing the responses of photoelectric cells to weak radiation. It is a variable, with a period of about 4 days, and an amplitude between maximum and minimum of 0.08 magnitude to 0.16 magnitude, depending on the spectral sensitivity of the measuring device. Its year-round availability and negligible diurnal motion are reasons for its choice over more constant stars.

the same temperature as the sun are selected. As is well known, the radiation curve of the sun is roughly that of a black body at 6000°K. The results for four detectors of radiation are given in Table I. These represent the limit reached in actual practice and not the theoretical limit. In the case of the photoelectric cell and thermocouple, for which the response is a "pointer reading," the criterion for limit of detection is taken as the average deviation of successive deflections from the mean when measuring a star near the useful limit of the instrument.

TABLE I

LIMIT OF DETECTION FOR STARS OF SOLAR TYPE

Detector	Exposure Time (minutes)	Telescope Diameter (inches)	Limiting Magnitude (visual)	Lumens ($\times 10^{-14}$)	Ergs/sec. ($\times 10^{-9}$)
Photographic plate[a]	240	5	16.3	0.8	0.5
Unaided human eye[b]	...	0.32	8.5	4	2.5
Photoelectric cell[c]	1	60	19.5	6	4
Thermocouple[d]	0.3	100	9.5	160,000	100,000

[a] Ross, F. E., and Calvert, Mary, *Atlas of the Milky Way*. Chicago: University of Chicago Press, 1934.
[b] Russell, H. N., *Astrophys. J.*, *45*, 60 (1917).
[c] Smith, S., *Astrophys. J.*, *76*, 486 (1932); *Mt. Wilson Contr. No. 457.*
[d] Pettit, E., and Nicholson, S. B., *Astrophys. J.*, *68*, 279 (1938); *Mt. Wilson Contr. No. 369.*

The data given in Table I are for response to a point source emitting "white" light, that is, light having the spectral quality of sunlight. For cases in which the image of the source cannot be made very small, the thermocouple must have larger receivers, and the limit is not as small as that given in the table by a factor of 5 to 10. The photographic plate also suffers when the source is an extended luminous

area, because the light is spread over a greater area on the emulsion. According to Biltz,[4] at 4360 Å it requires an energy of the order of 10^{-2} erg/cm^2 at the emulsion surface to give a perceptible blackening. The response of the photoelectric cell is independent of image size and shape as long as the image is not larger than the cathode. This gives it considerable advantage over the photographic plate in rapid measurement of low surface brightness.

The thermocouple, of course, measures energy independent of the spectral distribution of the light. The response curve of the human eye is given in Fig. 4, page 410. At the wave length of maximum visibility, 1 lumen $= 1.61 \times 10^{-3}$ watt. The variation of the sensitivity of various photographic plates with wave length is given by Mees.[5] The spectral response curves of various types of photoelectric cells are given on page 401. Assuming that the limit of detection is set by the smallest current that can be measured, these curves may be considered to give the limit of detection as a function of wave length. The case cited in Table I in which 4×10^{-9} erg/sec. was the limit probably represents a favorable instance. By choice of a suitable cell for each spectral region, the range from 2500 Å to 9500 Å can be covered with a limit of detection not greater than 10^{-7} erg/sec.

Types of cells. Two general types of cells have been found useful in the physical laboratory. One is the photoemissive cell, historically the oldest. In this type electrons are ejected from a metallic surface by the action of light and

[4] Biltz, M., *Phys. Zeits.*, *34*, 200 (1933). If the star image cited in Table I is assumed to be a round, uniformly illuminated spot 0.06 mm in diameter, the energy received at the plate is easily computed to be 0.25 erg/cm^2, or 25 times the figure given by Biltz. The difference may be ascribed to three factors: (1) Part of the radiation came in wave lengths to which the plate was insensitive. (2) The limit in stellar photography is set by lack of contrast between the star image and sky background. The sky brightness is so low that it does not affect other less sensitive detectors of radiation very seriously. (3) When the blackened area is very small, a higher density is required to make the image perceptible. Hubble, E., *Astrophys. J.*, *76*, 107 (1932); *Mt. Wilson Contr. No. 453.*

[5] Mees, C. E. K., *J. O. S. A.*, *21*, 753 (1931), *22*, 204 (1932), *23*, 229 (1933), *25*, 80 (1935).

are collected on an electrode maintained at a positive potential by an external battery. The other type is the photovoltaic cell, a comparatively recent development. In these cells light causes a transfer of electrons across the rectifying boundary between two dissimilar materials, such as copper and copper oxide, or selenium and another metal. The current is sent through the external circuit entirely by the voltage generated within the cell, and no battery is required.

A third type of light-sensitive device, the photoconductive cell, depends for its action on the change in resistance of certain materials, such as selenium, when exposed to light. Though greatly improved in recent years, these cells have not found much application in the physical laboratory. A serious drawback is the nonlinear response to light.[6]

Characteristics of emissive-type cells. The spectral sensitivity of various types of photoemissive cells is shown in Fig. 1. The relative height of the various curves is only approximately correct, since there is considerable individual variation in cells of the same type. The vertical scale is intended to represent the average emission of good-quality vacuum cells obtained from commercial manufacturers.

The cesium oxide cells are sensitive to the greatest range of wave lengths and are therefore probably the type most generally useful in the laboratory. This type of sensitization was developed to meet the need for a cell that would have a high response to light from incandescent tungsten bulbs, in which most of the energy comes in the red and infrared. Cesium oxide cells are very widely used in commercial applications of the photoelectric cell, such as for the reproduction of sound in motion pictures. Indeed, since their introduction in about 1930, the production of emission cells of other types has become almost negligible.

The cesium oxide cell has one drawback when it is used for measuring the light from very faint sources. It has relatively large dark current, due at least in part to thermionic

[6] For further information see Henney, K., *Electron Tubes in Industry*. Second Edition. New York: McGraw-Hill Book Company, 1937.

emission from the sensitive surface at room temperature. Currents as large as 10^{-9} ampere have been reported.[7] Present-day cells, when of a design which minimizes insulation leakage over the bulb and base, usually have a dark current of the order of 10^{-11} to 10^{-12} ampere. If the photocurrent is very much (say 1000 times) smaller than this, it

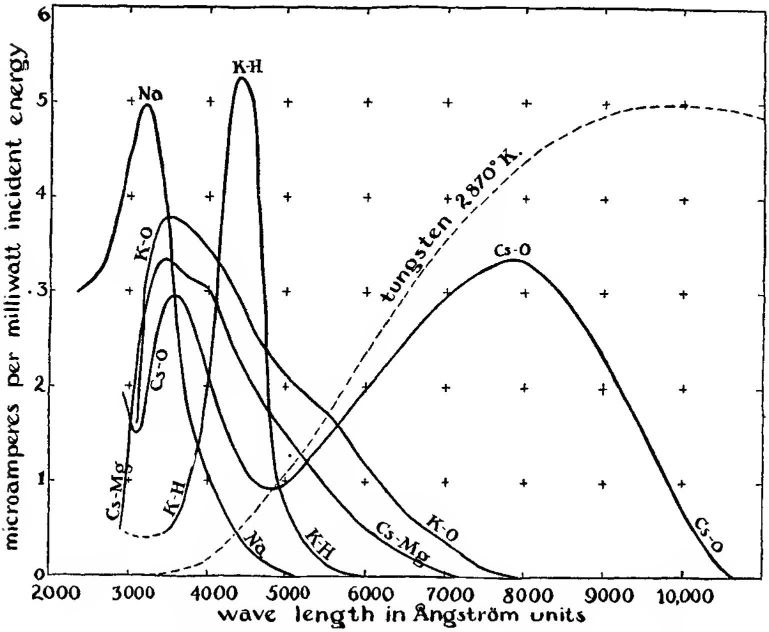

Fig. 1. Spectral sensitivity of various types of photoelectric cells.

will be masked by unavoidable irregularities in the dark current. The dark current can be reduced to 10^{-15} ampere or less by refrigerating the cell with solid carbon dioxide. This has been done by Hall[8] and Bennett[9] in their application of cesium oxide cells to the photometry of stars. Details of the design of such an arrangement are given on page 424.

In certain applications, the high infrared sensitivity of the

[7] Kingsbury, E. F., and Stillwell, G. R., *Phys. Rev.*, *37*, 1549 (1931).
[8] Hall, J. S., *Astrophys. J.*, *79*, 145 (1934).
[9] Bennett, A. L., *Pub. Am. Astr. Soc.*, *8*, 209 (1935).

cesium oxide cell is inconvenient. For example, in comparing the color of certain objects, it may be desired to measure the intensity through a blue filter. Almost all blue filters made of glass or gelatin are more or less transparent to the infrared, so that with a cesium oxide cell large error will be made unless an additional filter to remove the infrared is used. The standard filter for removing the infrared is a solution of copper salt.[10] Two special glass filters are also satisfactory. These are the Corning Glass Company's Aklo and the Jena BG-18.[11]

The potassium oxide cell is valuable in applications to colorimetry and photometry when infrared sensitivity is undesirable. Ordinary filters may be used with it, without particular attention to infrared leaks. It has a fair degree of red sensitivity, with a threshold at about 8000 Å, and a higher green and blue sensitivity than the cesium oxide cell. The thermionic emission is negligible. Cesium-magnesium cells are also useful for applications of this type. The threshold for this type of surface is at about 7000 Å.

Potassium hydride cells are sensitive to a fairly narrow range of wave lengths, mainly in the blue, with a maximum at about 4400 Å. Their sensitivity to white light and particularly to light from incandescent tungsten is considerably lower than for cesium oxide cells. However, in the photometry of stars, which are in general much hotter than incandescent lights and give out correspondingly greater amounts of blue light, potassium hydride cells have been found extremely valuable. For this work, an important advantage is their extremely low dark current, limited, it seems, only by the insulation of the bulb. Smith[12] has reported a dark current of only 5×10^{-18} ampere for a potassium hydride cell in a fused-quartz bulb.

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[10] Gibson, K. S., *J.O.S.A.*, *13*, 267 (1926), recommends 57 g of $CuSO_4 \cdot 5H_2O$ to 1 liter of water; about 2 cm is required. A transmission curve is given in Fig. 24, Chapter IX.

[11] Jena glass filters are obtainable from the Fish-Schurman Corporation, 250 East 43rd Street, New York City.

[12] Smith, S., *Astrophys. J.*, *76*, 486 (1932); *Mt. Wilson Contr. No. 457*.

For the ultraviolet the cesium oxide cell can be used. For applications in which the cell must be sensitive only to the ultraviolet, several types of cells are available, with different thresholds. Sodium cells are sensitive mainly to wave lengths in the range 2000 Å to 4000 Å, with a slight response to visible light. For the shorter wave-length portion of the ultraviolet a thorium, titanium, or tungsten cathode may be used. Thorium is sensitive from 2500 Å to 3600 Å, titanium from 2500 Å to 3200 Å, and tungsten from 1700 Å to 2700 Å. Insufficient data are available for plotting spectral response curves of these tubes along with those given in Fig. 1, but the response is believed to be comparable to that of a sodium cell at wave lengths below 3000 Å. These cells are especially useful in investigations of the biological effects of radiation.

In Table II is collected a representative list of photoelectric cells of the emission type obtainable from American manufacturers. When several cells which differ only as regards size of cathode or type of base are available, only one is listed. The sensitivity rating (except as otherwise noted) is based on the response to light from incandescent tungsten at a color temperature of 2870°K., which has been tentatively adopted as a standard source for comparing photocells. This is roughly the operating temperature of a 300-watt gas-filled tungsten bulb designed for general illumination purposes. When tested with a bulb at a lower temperature, cesium oxide cells will give a slightly higher apparent rating, but the rating of the blue-sensitive cells will be affected unfavorably. For rough tests gas-filled Mazda bulbs of from 50 watts to 100 watts may be used. At normal voltage these lamps have an efficiency of approximately 1.0 candle power/watt (within 10 to 20 per cent) and operate at about 2700°K.[13]

The insulation between cathode and anode is an important factor when a cell is to be used to measure a very faint source. If the insulation is not good enough, the dark current due to

[13] For further information see Moon, P. H., *Scientific Basis of Illuminating Engineering*. New York: McGraw-Hill Book Company, 1936.

TABLE II

PHOTOELECTRIC TUBES

Manufacturer's Type Number	Manu-facturer	Descrip-tion	Type of Cathode	Typical Sensitivity (Micro-amperes/lumen)	Base	Terminal on Bulb (if any)
PJ-14[a]	GE	vac	Cs-O	28	std	cathode
PJ-22	GE	vac	Cs-O	14	std	...
PJ-23	GE	gas	Cs-O	75	std	...
FJ-114	GE	vac	Cs-O	35	bayonet	...
71-AV	GM	vac	Cs-O	25	std	...
71-A	GM	gas	Cs-O	120	std	...
71-TA[b]	GM	gas	Cs-O	120	std	anode
1038-A[c]	GM	gas	Cs-O	120	none	...
5A	WE	vac	Cs-O	20	std	...
8A	WE	gas	Cs-O	100	std	...
D-97087	WE	gas	Cs-O	...	none	2 seals
917	RCA	vac	Cs-O	20	std	anode
918	RCA	gas	Cs-O	110	std	...
919	RCA	vac	Cs-O	20	std	cathode
920[d]	RCA	gas	Cs-O	110	std	...
CE-1	CE	gas	Cs-O	150	std	...
CE-15[b]	CE	gas	Cs-O	150	std	anode
WL-734	WH	vac	Cs-O	15	std	...
WL-735	WH	gas	Cs-O	60	std	...
SR-53	WH	vac	Cs-O	25	special	...
SR-63	WH	gas	Cs-O	125	special	...
WL-770	WH	vac	Cs-Mg	0.75	std	anode
WL-773	WH	vac	Th	0.10[e]	std	cathode
WL-767	WH	vac	Ti	0.02[e]	std	cathode
WL-774	WH	vac	W	0.001[e]	std	cathode
FJ-76[f]	GE	vac	Na	...	...	...
71-D	GM	gas	K-O	8[g]	std	...
...	...[h]	gas	K-H	3	...	...

Typical sensitivity is rating when exposed to tungsten light at 2870°K., except as otherwise noted. Std base means regular four-pin radio base. When no terminal on bulb is mentioned, both terminals come out through pins in the base. Manufacturers: GE, General Electric Company, Schenectady, New York; GM, G-M Laboratories, 1731 Belmont Avenue, Chicago, Illinois; RCA, RCA Manufacturing Company, Harrison, New Jersey; WH, Westing-

house Lamp Company, Bloomfield, New Jersey; CE, Continental Electric Company, Geneva, Illinois.

[a] Listed as "special high sensitivity cell similar to PJ-14."

[b] High insulation cell with internal guard ring.

[c] Quartz bulb; terminals through common seal, but special sheath provided.

[d] Twin cell. Two cathodes and two anodes in single bulb.

[e] Response to total radiation from S-1 lamp in Corex bulb, with standard reflector, at a distance of 1 foot.

[f] Quartz bulb; also available in gas-filled type.

[g] Not manufacturer's figure; estimated from other data.

[h] As far as is known, this type of cell is not now regularly produced by any American commercial manufacturer, although it might be obtained on a special order. Those used in astronomical photometry have been made by Professor J. Kunz, Department of Physics, University of Illinois. The General Electric Company, Ltd., Magnet House, Kingsway, London, W. C. 2, manufactures a gas-filled potassium cell known as the Osram KG-7.

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leakage may be many times larger than the photocurrent. For example, in certain cells designed for use in the sound head of motion-picture projectors, in which the photocurrent may be on the order of 1 microampere, the two terminals come out to pins on a standard four-prong radio-tube base. In general, cells of this type are not satisfactory for currents smaller than about 10^{-10} ampere. In some cells the connection to either the cathode or the anode is made via a separate cap on the bulb, and thus a considerable length of clear glass bulb is interposed between the terminals to serve as insulation. Cells without a base in which the terminals come out through a common pressed seal are better than those with a base, but not as good as those in which there are two seals at opposite ends of the bulb.

In many cases the leakage current over the surface of the bulb can be practically eliminated by a guard ring at a proper place on the cell. This can be made by wrapping a few turns of fine wire around the cell and painting with aquadag[14] or a mixture of lampblack and mucilage. The guard ring should be connected to a point in the circuit such that the potential difference across the insulation on the cell will be as near zero as possible. In some processes of manufacture, particularly of cesium oxide cells, a thin deposit is left on the

[14] Aquadag is obtainable from the Acheson Colloids Corporation, Port Huron, Michigan.

inside walls of the bulb, which greatly reduces the insulation resistance. The obvious remedy is an internal guard ring, and some manufacturers regularly provide this feature on certain of their cells.

In general, insulation leakage currents are greatly reduced by cooling, because of the quasi-electrolytic nature of such conduction. For instance, the dark current of an RCA 917 cell fell from about 10^{-10} ampere to about 10^{-13} ampere when cooled with dry ice. The latter current is not a serious detriment except when the highest sensitivity is required. It thus becomes possible to use an inexpensive commercial cell to measure rather faint sources. A suitable arrangement for refrigerating cells with dry ice is described on page 424.

The manufacture of cells. The prospective user of photoelectric cells will find it by far the most economical procedure as regards both time and money to purchase the cells from an established manufacturer. The production of highly sensitive cathodes is still very much an art which has never been fully described in the literature and requires some experience to master. Most manufacturers will accept orders for special cells with internal guard rings or other modifications required in particular applications.[15]

Vacuum and gas-filled cells. In vacuum cells the anode merely collects all of the electrons ejected from the light-sensitive cathode. The current for a given light increases rapidly with voltage up to about 25 volts and then gradually becomes saturated and does not increase further. The introduction of an inert gas at a pressure of a few tenths of a

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[15] For workers who wish to experiment with the making of cells, the following references will give fairly complete instructions:

Hughes, A. L., and DuBridge, L. A., *Photoelectric Phenomena*. McGraw-Hill Book Company, 1932. Chapter 12 gives a summary of methods for all types of cells.

Nottingham, W. B., *Frank. Inst., J.*, *206*, 637 (1928). Details for alkali-hydride cells.

Prescott, C. H., Jr., and Kelley, M. J., *Bell System Techn. J.*, *11*, 334 (1932). Detailed analysis of the process for cesium oxide cells.

Rentschler, H. C., Henry, D. E., and Smith, K. O., *Rev. Sci. Instruments*, *3*, 794 (1932). Deposition of thorium, tungsten, and many other metals on the cathode by a sputtering process.

millimeter permits an amplification of the original photocurrent due to ionization by collision. Fig. 2 shows the relation between the voltage and the current for the same sensitive surface in a vacuum and with gas. With increasing voltage the gaseous amplification factor increases until at a certain voltage a self-maintaining glow discharge sets in, which, if continued for more than a few seconds, may seriously damage the sensitive surface. The glow voltage is lower the greater the illumination. Thus a cell which is

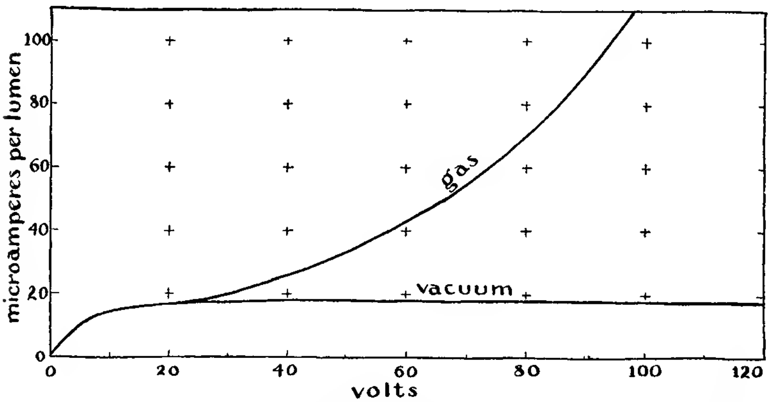

Fig. 2. Volt-ampere characteristics of vacuum and gas-filled photoelectric cells.

safely below the glow voltage in the dark or for low illumination levels will glow when exposed to strong light. A gaseous amplification factor of 10 is about the maximum usually recommended. The gas pressure in commercial cells is usually adjusted so that 90 volts is the maximum safe voltage on the cell for illumination of the order of 0.1 lumen. However, when used with faint sources, this may be exceeded somewhat and an amplification factor of 20 to 40 realized. When a voltage increase of 10 volts doubles the response, the safe limit has been reached. Amplification factors as high as 600 have been reported,[16] but a gas cell becomes very unstable when too near the glow voltage.

[16] Steinke, E., *Zeits. f. Physik*, *38*, 378 (1926).

A protective resistance of at least 100,000 ohms should always be in the circuit of a gas-filled cell to limit the current to nondestructive values in case of a glow discharge.

The speed of response of a vacuum cell is limited only by the transit time of the photoelectrons, though usually the amplifier sets the limit. Gas-filled cells, however, have a definite time lag. When used with a modulated light signal, the response falls off gradually at the higher audio frequencies, the reduction becoming serious at 10,000 cycles. Data on the frequency response characteristic are supplied by cell manufacturers, particularly for cells to be used in sound reproduction.

When operated on the steep part of the current-voltage curve, gas cells may give a nonlinear response to light. The voltage across the cell is reduced when exposed to light by the amount of the potential drop in the external resistance, and with reduced voltage, the cell is less sensitive. On the other hand, the gaseous amplification factor is greater for more intense illumination, causing an error in the opposite sense. No general rule can be laid down; each situation must be analyzed separately. In most laboratory applications, however, in which the intensity is usually low, difficulties with nonlinear response are less likely to be encountered. In fact, most of the drawbacks of gas-filled cells become less serious when used with faint sources. Recently Stebbins and Whitford[17] calibrated a gas-filled potassium hydride cell over a thousandfold range in intensity at a constant cell voltage. The largest current was about 3×10^{-12} ampere. They found no departures from linearity significantly greater than the probable error, which was about 1 per cent.

Photoelectric currents are feeble enough at best, and the gain provided by gaseous amplification is often just the margin of safety between satisfactory and unsatisfactory

[17] Stebbins, J., and Whitford, A. E., *Astrophys. J.*, *87*, 237, 1937; *Mt. Wilson Contr. No. 586.*

operation. However, when the light intensity is great enough, vacuum cells are to be preferred because of their greater stability.

Photovoltaic cells. In its usual form the photovoltaic cell consists of a thin metallic disk, coated with a film of sensitive material, sealed in a moisture-proof case with a glass window, and provided with suitable terminals. On some cells the terminals are two pins spaced to fit two of the holes of a standard four-prong radio socket. Cells of the photovoltaic type are manufactured by the General Electric Company, G-M Laboratories, Inc., Westinghouse Electric and Manufacturing Company (Photox), and Weston Electrical Instrument Corporation (Photronic cell).

Fig. 3 shows the relation between current output and illumination for the Weston Photronic cell with various

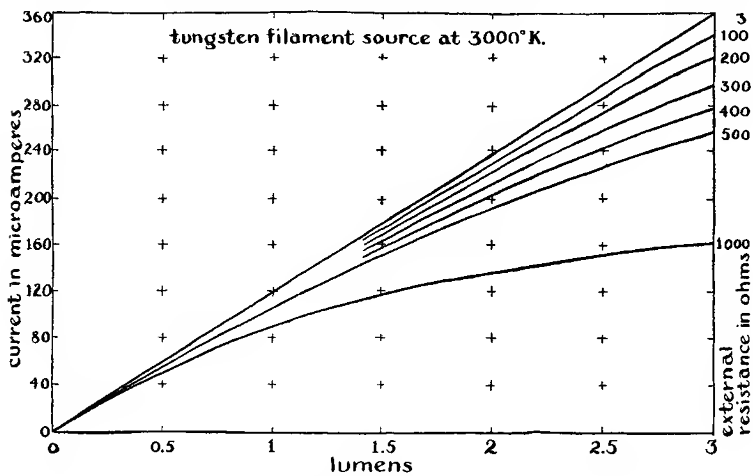

Fig. 3. **Response of Photronic cell as a function of illumination for various values of the external resistance.**

external resistances. The total current generated by the light is believed to be proportional to the light intensity. However, this current divides between the internal and external resistance. The internal resistance of the cell is about 7000 ohms in the dark, decreasing rapidly with

increasing illumination.[18] As the figure shows, the result is a nonlinear current output unless the external resistance is quite small. With a low-resistance meter, however, the output is practically linear and amounts to 120 microamperes/lumen for a tungsten lamp at 3000°K.

The spectral sensitivity curve of the Photronic cell is shown in Fig. 4, along with the sensitivity curve of the

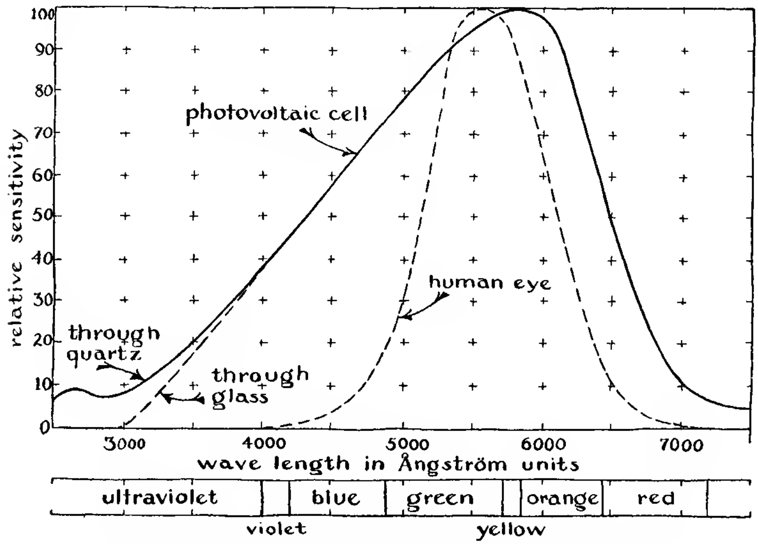

Fig. 4. Spectral sensitivity of Photronic cell, compared with that of the human eye.

human eye. By use of a suitable filter, the response curve of the cell may be modified to match that of the eye very closely. Such a filter is supplied by the makers of the cell.

The photovoltaic cell, when used with a sensitive d'Arsonval galvanometer, gives very stable and reproducible deflections. If the Photronic cell mentioned above were used with a galvanometer having a current sensitivity of 2×10^{-10} ampere/mm, 1 mm would correspond to 1.7×10^{-6} lumen. The sensitive area of the cell is about 0.012 square foot. From this it may be computed that 1 mm deflection would

[18] Romain, B. P., *Rev. Sci. Instruments*, *4*, 83 (1933).

correspond to the amount of light received by the cell from a standard candle at 85 feet. A slight gain might be realized by using a more sensitive galvanometer, but it is not worth while to push the sensitivity to the extreme limit, because of the comparative ease with which much smaller amounts of light may be measured with an emission-type cell and amplifier.

Amplification of the output of photovoltaic cells is not feasible, because of their low voltage sensitivity.[19] Because of the high capacity (0.5 microfarad) between the terminals, the response to modulated light intensities falls rapidly with increasing frequency, and the cell is not well adapted to sound reproduction. The power sensitivity is high and a sensitive relay can be operated directly on the output if there is a change in illumination of 0.2 lumen or more.[20] In many applications of the photoelectric cell to automatic control mechanisms, in which only an on-and-off signal is required, this is a simple and convenient arrangement.

For laboratory measurements, the photovoltaic cell is recommended in applications in which there is sufficient intensity available, because of its simplicity and compactness, and because it does not require an external battery.

Amplification of photoelectric currents. Photoelectric cells of the emission type may be used with galvanometers down to about the same limit of light intensity as that given above for photovoltaic cells. For fainter sources some more sensitive current-measuring device must be used. Electrometers of various types can be used, and in certain applications may be the most desirable instrument. In particular, the Lindemann electrometer, or the Cenco-Dershem modification of it, is useful when light weight and compactness are important considerations. In the last few years, however, it has increasingly been the practice to amplify small photo-

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[19] Wilson, E. D., *Rev. Sci. Instruments*, *2*, 797 (1931).

[20] Suitable relays are manufactured by the Weston Electrical Instrument Corporation and the G-M Laboratories, Inc.

electric currents up to the level at which they can be read on a galvanometer. The advantages of amplification are that (1) currents which must be measured by the rate-of-drift method with an electrometer can be measured by the more convenient steady-deflection method, and (2) the amplifier is more rugged and portable than the electrometer. But for attaining the ultimate limit in measuring photoelectric currents, the Hoffmann electrometer is probably still the best instrument.

In case the photoelectric current is varying rapidly with time, the variations can easily be amplified many thousand-fold by means of a multistage a.c. amplifier, the technique for which has been highly developed because of numerous applications in the radio, telephone, and motion-picture industries. In the laboratory, however, it is usually desired to measure the photoelectric current due to a steady source. Hence d.c. amplification must be used.

Direct-current amplifiers. The fundamental circuit of a single-tube d.c. amplifier is shown in Fig. 5. The photo-current passes through a resistance R_0, and the resulting

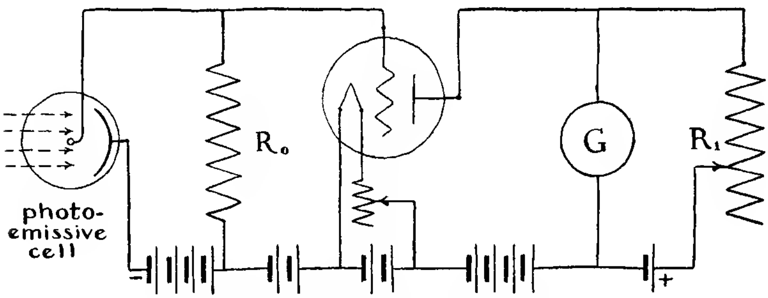

Fig. 5. Direct-current amplifier for photocurrents.

voltage drop alters the grid potential of the tube. The consequent change in plate current is read on the galvanometer. The normal plate current of the tube is balanced out by adjustment of R_1 so that the galvanometer reads zero when there is no light on the cell. Since R_1 is usually at least fifty times the galvanometer resistance, the galva-

nometer will indicate very nearly the entire change in plate current. If i_0 is the photocurrent, the galvanometer current i_1 is then $i_1 = i_0 R_0 g_m$, where g_m is the mutual conductance of the tube. The mutual conductance, more correctly called the grid-plate transconductance, is defined by the relation $g_m = di_p/de_g$, where i_p is the plate current and e_g is the grid voltage. To obtain high current amplification it is necessary to make R_0 as great as possible. It is useless, however, to increase R_0 indefinitely, because it is shunted by the grid-to-filament resistance of the tube itself. With most tubes designed for use in radio receivers this resistance is not over 10^8 ohms. The instability of the plate current is such that it is not worth while to use a galvanometer with a sensitivity better than 10^{-8} ampere/mm. Such a circuit is therefore limited to measuring currents greater than 10^{-12} ampere.

The comparatively low value of the grid-to-filament resistance in ordinary tubes is due not so much to poor

TABLE III

RECOMMENDED OPERATING CONDITIONS AND OTHER ESSENTIAL DATA FOR TWO MAKES OF ELECTROMETER TUBES

	FP-54	D-96475
Filament voltage	2.5 volts	1 volt
Filament current	0.09 ampere	0.27 ampere
Space-charge grid voltage	4 volts	4 volts
Plate voltage	6 volts	4 volts
Control grid voltage	4 volts	3 volts
Input resistance	10^{16} ohms	10^{16} ohms
Control grid current	10^{-15} ampere	10^{-15} ampere
Plate current	60 microamperes	85 microamperes
Plate resistance	45,000 ohms	25,000 ohms
Mutual conductance	20 microamperes/volt	40 microamperes/volt

insulation as to charges reaching the grid inside the tube. Any variation of the grid current with voltage constitutes a conductance. Metcalf and Thompson[21] made a systematic study of the sources of current to the grid and methods of

[21] Metcalf, G. F., and Thompson, B. J., *Phys. Rev.*, *30*, 1489 (1930).

eliminating or reducing them. As a result, a new tube known as the FP-54 was developed especially for the amplification of small direct currents. It is made by the General Electric Company. The Western Electric Company makes a similar tube, known as the D-96475. These tubes have an inner space-charge grid to shield the control grid from positive ions emitted by the filament. They are operated at a very low plate voltage to avoid ionization of the residual gas.

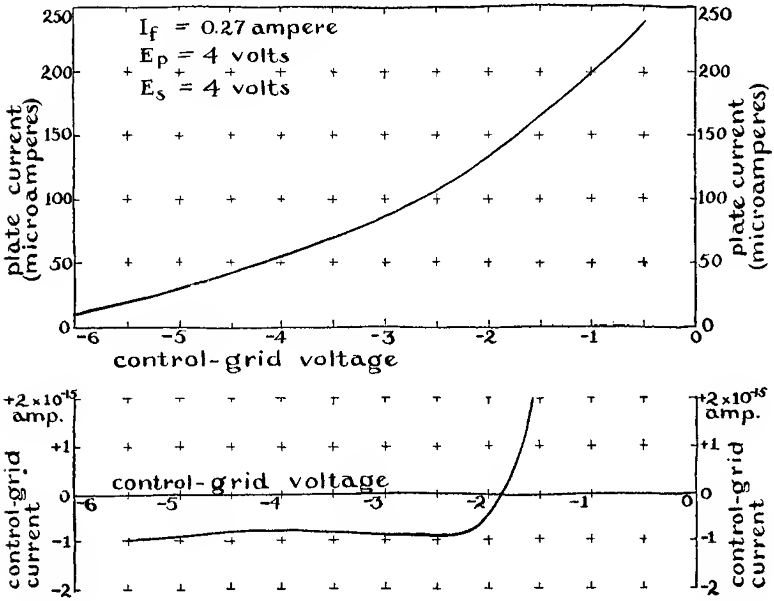

Fig. 6. Plate- and grid-current characteristics of Western Electric D-96475 tube.

Because they replace an electrometer, they are often called electrometer tubes. Their grid resistance is approximately 10^{16} ohms.

The recommended operating conditions and other essential data for the two makes of electrometer tubes are shown in Table III.

Characteristic curves showing the plate current and control grid current of a typical D-96475 tube are set forth in Fig. 6. The slope of the grid-current curves gives the grid

conductance, and the reciprocal of the slope is the grid resistance. The control grid is operated at − 3 volts, because the curve is nearly flat at that point. The slope of the plate-current curve gives the mutual conductance. The curvature of the plate-current curve is quite noticeable, and is sufficient to cause appreciable nonlinearity if the grid voltage changes by 0.1 volt, a rather large change in most applications.

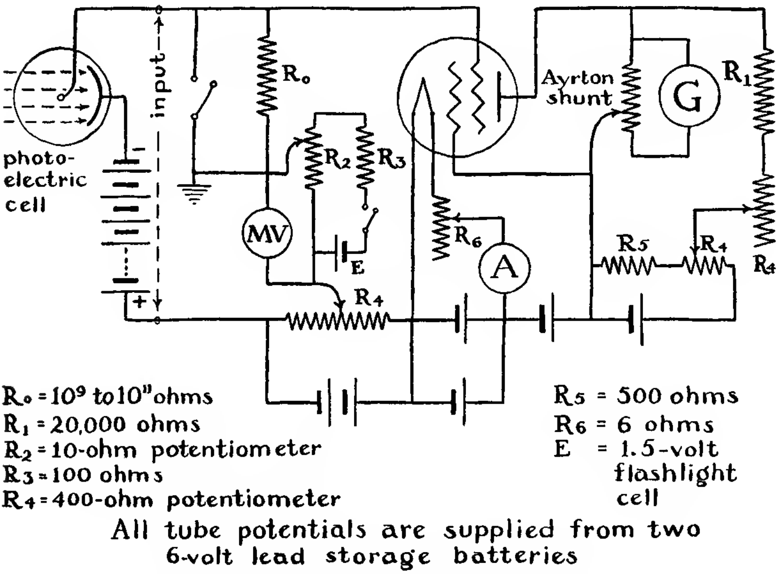

Fig. 7. Circuit for amplification of photocurrents using the D-96475 tube.

Fig. 7 gives in detail the constants of a simple circuit employing the D-96475 for the measurement of the photoelectric currents. By choosing a resistance R_0 of the proper value, and varying the galvanometer shunt, a very wide range of currents may be covered. The calibration circuit in the control-grid lead provides a means of testing the sensitivity, which should be of the order of 100,000 mm/volt for a galvanometer sensitivity of 4×10^{-10} ampere/mm.

The stability of the plate current in such a circuit of course determines the smallest current that may be measured. A slow drift in the galvanometer zero will not cause a serious

loss in accuracy if the rate is constant during the time of one observation, since it may easily be averaged out by taking alternate zeros according to a definite schedule. In certain applications of electrometer tubes, such as measurement of α particles, when continuous registration over long periods is required, a very low drift rate is necessary. In any case it is desirable to reduce drift as much as possible.

Random fluctuations of the zero, on the other hand, place a definite limitation on the useful sensitivity of the amplifier. These may be due to external conditions, such as mechanical vibration, poor insulation, poor contacts, stray electric and magnetic fields, or residual atmospheric ions settling on the grid lead. By suitable precautions, disturbances due to such causes can be practically eliminated. There remain inherent and unavoidable fluctuations caused by variations in filament emission and by shot effect and Johnson effect (thermal noise) in the grid circuit. In actual practice, uneven filament emission is found to be unimportant compared to the two latter sources of fluctuations. A quantitative discussion of these factors is reserved for a later paragraph.

Contrary to statements which have appeared in the literature, battery potential fluctuations are not a limiting factor in using a simple circuit of the type shown in Fig. 7. The stability is determined in the grid circuit, as is shown by the fact that the zero is much steadier with the high resistance R_0 shorted out. The effects of variable filament emission remain. To gauge the effect of the battery fluctuations only, the tube may be removed and replaced by fixed resistances equivalent to the filament resistance and to the static filament-to-plate resistance. The galvanometer will then be perfectly steady, except possibly for a slow uniform drift, showing that there are no sudden changes in battery voltage large enough to affect the stability.

One cause of drifts is temperature variation, which changes battery voltages and the resistance of various parts of the circuit. If the temperature is constant, the galvanometer in the circuit shown in Fig. 7 drifts slowly in the direction of

decreasing plate current. This is caused mainly by a decrease in the filament current as the battery discharges. The larger the filament battery the slower the drift—hence the paralleling of cells in Fig. 7. As soon as equilibrium is reached, the rate of drift is less than 1 mm/minute at a sensitivity of 100,000 mm/volt. For most laboratory measurements such a rate is not a serious drawback.

The simplest method of controlling drift is to introduce a counterdrift whose rate can be adjusted. Hafstad[22] placed

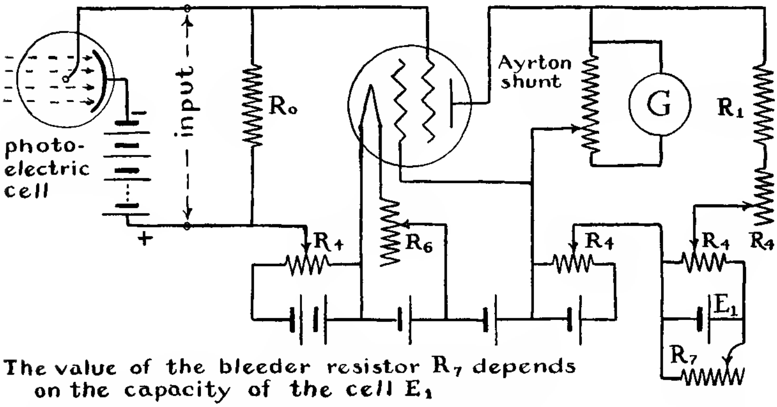

Fig. 8. Control of drift by introducing adjustable counterdrift in plate circuit. Resistances have the same values as in Fig. 7.

a countercell in the filament circuit and bled it with a variable resistance. A smaller cell is required if the counterdrift is introduced in the plate circuit. An arrangement of this type, similar to one described by Bearden,[23] is shown in Fig. 8. Part of the voltage which balances out the plate current of the tube comes from the cell E_1, which is being discharged through R_7. The discharge rate is set so that if all the voltage for balancing out were taken from E_1, the drift would be in the direction of increasing plate current. Then by varying the amount of voltage taken from the loaded and unloaded cell, the normal drift due to decreasing

[22] Hafstad, L. R., *Phys. Rev.*, *44*, 201 (1933).
[23] Bearden, J. A., *Rev. Sci. Instruments*, *4*, 271 (1936).

plate current may be compensated. The advantage of this method is that the drift rate may be changed immediately without altering anything in the circuit that requires some time to reach a new equilibrium. The cell E_1 may be a flashlight cell, or if a rechargeable cell is desired, an Edison storage cell. In cases where the tube is to be operated continuously over long periods, the cell E_1 may be eliminated and the battery discharging resistor attached directly to the last cell of a storage battery. The drift rate is then regulated by varying the discharge current. This requires some patience to adjust.

Numerous circuits have been devised with a view to making the plate current of a vacuum tube independent of small changes in supply voltage. The former two-tube circuits[24] required tubes with matched characteristics, which are often difficult to obtain. Recently practically all balanced circuits have consisted of a single tube in a suitable resistance network.

The single-tube circuit originated by DuBridge and Brown[25] has been successfully used in many laboratories.

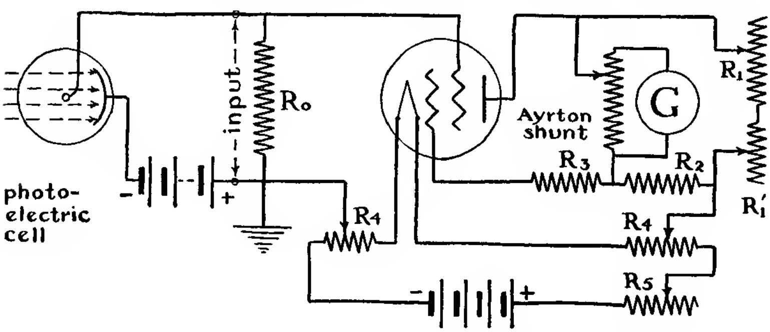

Fig. 9. DuBridge and Brown's balanced circuit for the FP-54 tube.

It is shown in Fig. 9. It can be regarded as a Wheatstone bridge in which R_1 and R_2 form two of the resistance arms,

[24] DuBridge, L. A., *Phys. Rev.*, *37*, 392 (1931).
Wynn-Williams, C. E., *Phil. Mag.*, *6*, 324 (1928).

[25] DuBridge, L. A., and Brown, H., *Rev. Sci. Instruments*, *4*, 532, 1933. See Turner, L. A., *Rev. Sci. Instruments*, *4*, 665 (1933), for other circuits.

and the filament-to-plate resistance and filament-to-space-charge-grid resistance form two other arms. The resistance R_3 may be considered a part of the tube resistance. A condition that the galvanometer current be zero is obviously

$$R_1 I_p = R_2 I_s.$$

In order for this condition to remain satisfied when the battery voltage changes, or the filament emission changes for any reason, it is further necessary that

$$\frac{dI_p}{dI_f} = \frac{R_1}{R_2} \cdot \frac{dI_s}{dI_f}.$$

For these conditions to be satisfied in general, it would be necessary for the I_p versus I_f and I_s versus I_f curves to be straight lines intersecting at a common point on the I_f axis. Of course, the tubes do not have this characteristic, but over short ranges the tangents to the I_p and I_s curves do satisfy this condition, and it is possible to adjust the resistances in the circuit so that this can be made to occur at approximately the rated filament current.

The resistance R_3 is necessary to provide a voltage drop of 2 volts, since the space-charge-grid voltage of the FP-54 is 4 volts and the plate voltage is 6 volts. For the D-96475 tube, in which both the space-charge-grid and the plate operate at 4 volts, it would be omitted. In a typical setup with the FP-54 tube, R_6 was 45 ohms, R_3 was 4000 ohms, R_2 was 2000 ohms, and R_1 was a 10,000-ohm rheostat, with R_1' a 50-ohm rheostat for fine adjustment. R_4 was a 50-ohm potentiometer. The procedure in balancing the circuit is as follows: With the galvanometer shunted to one tenth or one hundredth of its full sensitivity and R_1 adjusted so that the galvanometer reads zero when I_f is near its rated value, I_f is slowly varied by means of the rheostat R_5. With the galvanometer connected so that a positive deflection is caused by a decrease in the plate current, the deflection should pass through a maximum value for some value of I_f. If the galvanometer deflection goes off scale before the maxi-

mum is reached, it may be brought back by an adjustment of R_1.

If the value I_f for maximum is not within a few per cent of the rated value for the tube, the adjustment of R_4 and R_1 will bring the balance point to a different value I_f. The adjustment is finally made with the galvanometer at full sensitivity. Each adjustment will require a few minutes' waiting for a new thermal equilibrium to be established.

The advantage of this ingenious circuit is that any change in the filament emission due to variation in battery voltage or deactivation of the filament is compensated. Also short-period fluctuations in the filament emission are balanced out, and the stability with R_0 shorted out is somewhat improved over that obtained with the circuit of Fig. 7.

Some workers have experienced difficulty in obtaining the balanced condition for tubes of different characteristics. Penick[26] has given a thorough analysis of balanced circuits, with special application to the D-96475 electrometer tube. He suggests a modification of the DuBridge and Brown circuit which in effect amounts to attaching the leads from the plate and space-charge-grid leads of the bridge to separate taps on the resistance R_4. In practice this is best done by using two potentiometers in parallel. This introduces an additional element of flexibility in the circuit and enables a balance point to be reached for tubes of widely different characteristics. However, there are considerable individual variations in electrometer tubes, and sometimes with a particular tube it may not be possible to reach a balance point with reasonable values for the other circuit constants.

The best type of circuit for a particular application must be decided upon the basis of the conditions of use. The limiting sensitivity obtainable is about the same for all types of circuits. A balanced circuit is probably preferable when the use is to be irregular or intermittent because of much shorter warm-up time. A simple uncompensated circuit

[26] Penick, D. B., *Rev. Sci. Instruments*, *6*, 115 (1935). Full references to the literature are given.

requires several hours to reach equilibrium. However, if it is to be used daily, there is no objection to letting the filament run continuously.

In applications in which the circuit is to be used for both steady deflections and rate-of-drift measurements, the balanced circuit becomes rather complicated, because whenever the control-grid bias is changed, in order to find equilibrium potential the entire circuit must be rebalanced.

In order to reach high sensitivity by the steady-deflection method the resistance R_0 must be made very large. If it is much larger than 10^{11} ohms, the time constant of the input circuit becomes unduly long, and considerable time is wasted in waiting for deflections to reach their final value. The highest sensitivity is best obtained by the rate-of-drift method. To do this the anode of the photoelectric cell (or other sources of the current to be measured) is connected directly to the control grid of the tube with no other resistance. A high-insulation switch free from contact potentials is necessary for grounding the grid. When the tube is operated at the rated control-grid voltage, the grid current is approximately 10^{-15} ampere. If the grid is "floated" by opening the grounding switch, it will draw this current and drift in the direction of less negative grid potential. In order to eliminate this drift, the grid bias must be changed to such a value that the positive and negative components of the grid current are equal and the grid current is zero. When operating at this so-called "equilibrium potential," the grid resistance, as shown by the slope of the lower curve in Fig. 6, is considerably reduced but is still usually as high as 10^{14} ohms and is quite satisfactory for use in the rate-of-drift method. The equilibrium potential is found by observing the drift when the grounding switch is opened for various values of the control-grid potential until a value sufficiently near zero drift is reached. The galvanometer must be brought back to zero after each change in the grid bias, by adjustment of the resistance in the plate circuit. The procedure for measuring a small photoelectric current is then

to observe the drift rate with the light alternately on and off. This may be done by timing the drift over a particular interval of the galvanometer scale, but better results will be obtained if the galvanometer deflections are continuously recorded photographically. The value for the slope of the drift curve does not then depend on observations at two particular points. In fact, in all measurements in which the inherent fluctuations set the observing limit, improved accuracy will be obtained with photographic registration.[26a]

Measurements made by the rate-of-drift method may be connected with steady-deflection measurements by measuring the same current by both methods. In effect this constitutes a measurement of the capacity of the grid circuit.

Experimental details. The photoelectric cell and electrometer tube must be enclosed in a light-tight metal box. If high sensitivity is required, the container should be evacuated in order to eliminate the effect of residual ions in the air caused by cosmic rays. A suitable form for the container consists of a brass cylinder with a light window on the side. The amplifying tube and photoelectric cell are best supported entirely from one end plate in order to facilitate removal for adjustment. The vacuum seal may be made with a rubber gasket. A vacuum of the order of 1 mm of mercury is sufficient. The necessary switching arrangements can be operated by means of cams on a shaft which turns through a conical ground joint in the end plate. A separate metal shield over the tube inside of the container is advisable, and this may be made to serve also as a light shield to screen the photoelectric cell from the light of the filament. In case the container is not evacuated, it should be kept dry by the use of calcium chloride or phosphorus pentoxide.

A satisfactory design for mounting the cell and tube in an evacuated brass tank is shown in Fig. 10. The diagram is largely self-explanatory. The construction of vacuum tanks, valves, and gaskets is treated in Chapter III.

[26a] A suitable optical arrangement for photographic recording of galvanometer deflections is shown in Fig. 47, Chapter IX.

When a cesium oxide cell must be refrigerated to reduce the thermionic emission, the design shown in Fig. 11 meets the requirements. Here the problem is to have the cell as cold as possible, but to keep the light window from fogging

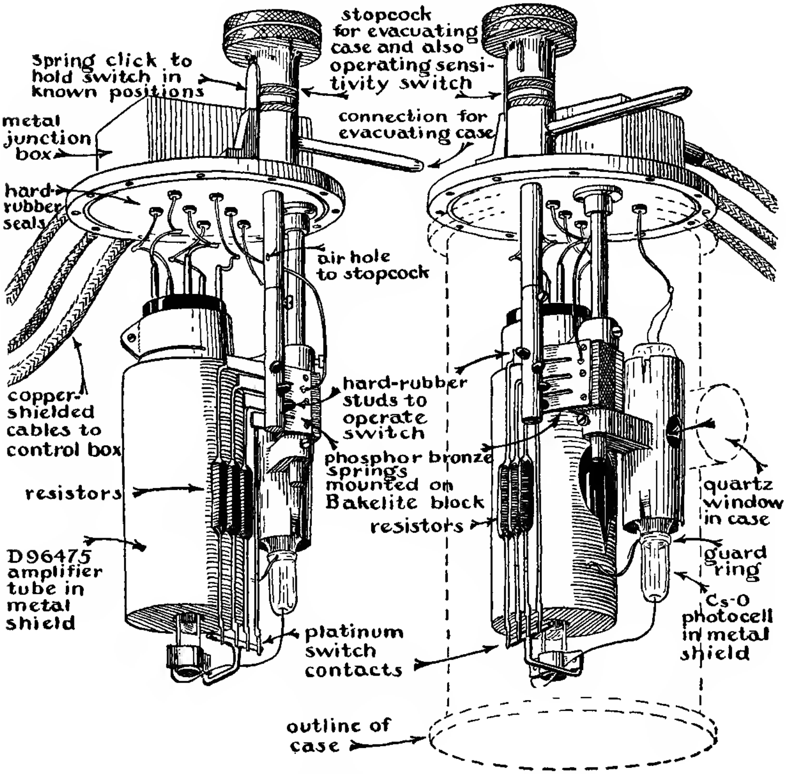

Fig. 10. Method of mounting photocell and electrometer tube in evacuated brass tank. (If circuit is grounded at the usual point, as in Fig. 7, the Bakelite insulation of the phosphor-bronze springs is unnecessary. They may be attached directly to the brass post as shown in Fig. 11.)

and the wax seals from becoming too cold and brittle. This necessitates some rather steep thermal gradients, which are successfully withstood by the Pyrex tube around the cell. To maintain isothermal conditions, the dry-ice compartment is made of sheet copper, and the Pyrex tube is sheathed with copper.

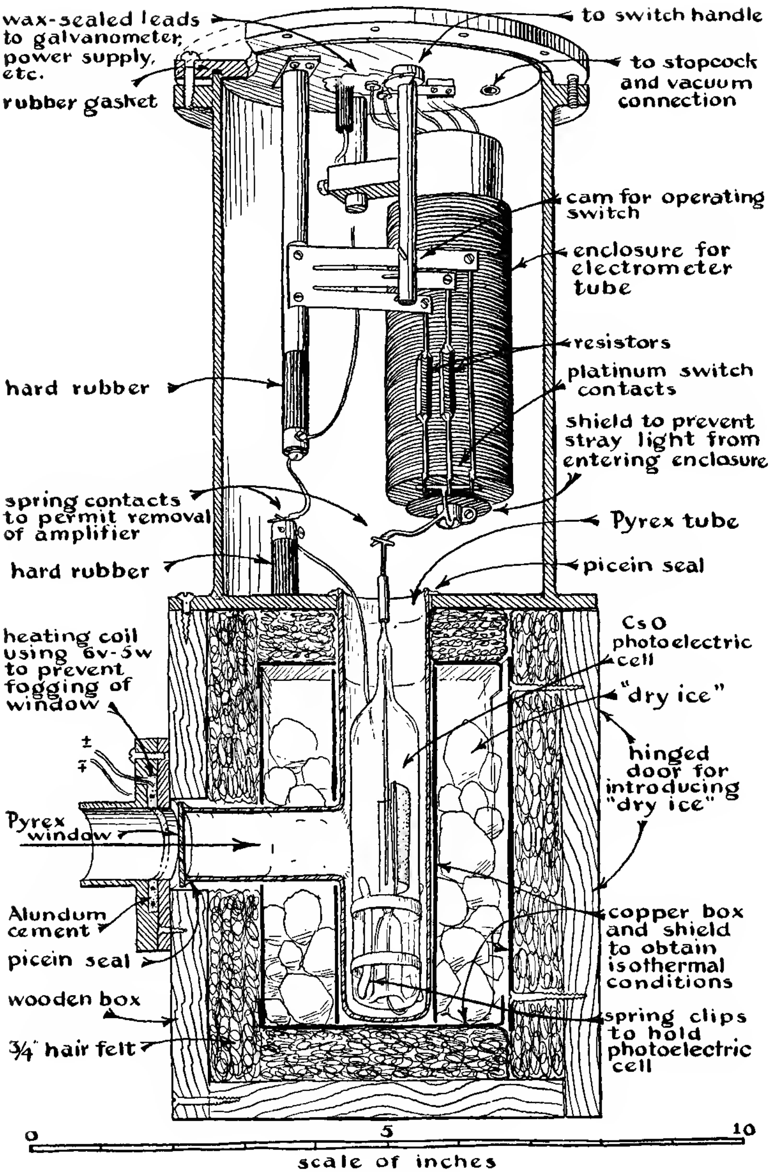

Fig. 11. Evacuated container for photocell and electrometer tube, with provision for refrigerating the cell to reduce thermionic emission.

In both Fig. 10 and Fig. 11 is shown a convenient switching arrangement which provides the possibility of using any one of three grid resistors, or of floating the grid for rate-of-drift measurements. This design requires no other support for the sensitive grid lead than that furnished by the tube itself. Should other support be necessary, only the best insulating materials should be used. Amber or fused quartz is recommended. All insulating surfaces, including the photoelectric cell and the exterior of the amplifying tube, must be kept free from grease or dirt and should be handled as little as possible. They may be cleaned by swabbing with cotton moistened with 95 per cent ethyl alcohol.

All parts of the circuit should be enclosed in metallic shielding. The various control resistances, the galvanometer shunt, and necessary meters may be mounted in a metal or metal-lined box such as that shown in Fig. 12.

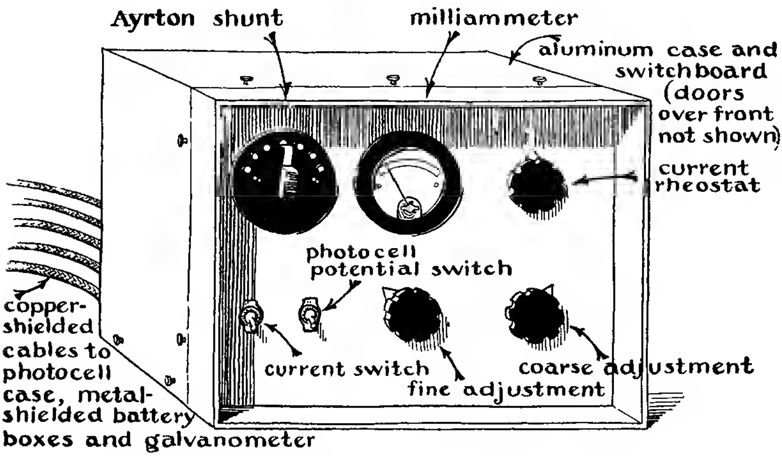

Fig. 12. Control box for electrometer tube circuit.

Placing the battery in a shielded box is also advisable. Temperature insulation on this box to cut down drifts will be helpful. The shielded multiconductor cables available from radio supply houses will be suitable for connections

between these various units, or the necessary wires may be pulled through a flexible metal hose.[27]

Whenever possible, all connections should be soldered, using only rosin flux. A flux made by dissolving rosin in alcohol will be found convenient; it may be applied with a brush. It is usually not necessary to solder the wires to the pins of the tube base, but a socket which grips the pins tightly must be used. The soldering of connections to the battery terminals is particularly important.

The batteries should be kept in first-class condition; the tops should be kept clean and dry. They should be charged at a moderate rate. It will be found advantageous to operate them only on the middle portion of the discharge curve.

The resistances, rheostats, and potentiometers should be of good quality. Wire-wound resistors may be obtained from any radio supply house. General Radio Type 371 potentiometers have been found satisfactory. Ohmite model H and model J units are also to be recommended. The inexpensive small wire-wound potentiometers of the type used in radios are not above suspicion, but Clarostat controls have been found entirely satisfactory by some workers. The high resistances to be used in the control-grid circuit are supplied commercially with values up to 10^{12} ohms.[28] These resistors have proved so satisfactory that it is not worth while for the worker to attempt to make his own.

In certain applications, in which portability is required or vibration makes it difficult to use a sensitive galvanometer, an additional stage of amplification may be necessary. DuBridge[29] used a 112A triode for the second stage and obtained an over-all current amplification of 4×10^7. The indicator was a microammeter. The design of the second stage is not critical, and almost any tube with a high mutual conductance is satisfactory. However, for most laboratory

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[27] Such hose is obtainable from the American Metal Hose Company, Waterbury, Connecticut.

[28] These resistors may be purchased from the S. S. White Dental Manufacturing Company, Industrial Division, 10 East 40th Street, New York City.

[29] DuBridge, L. A., *Phys. Rev.*, *37*, 392 (1931).

applications a single electrometer tube and galvanometer is preferable. A galvanometer with a sensitivity of 5×10^{-10} ampere/mm at 1 m is simple and foolproof, and amply sensitive to show the inherent unavoidable fluctuations of the amplifier.

Other low-grid-current tubes. Several workers have pointed out that many commercial radio tubes, when operated at low potentials, have greatly reduced grid currents, and

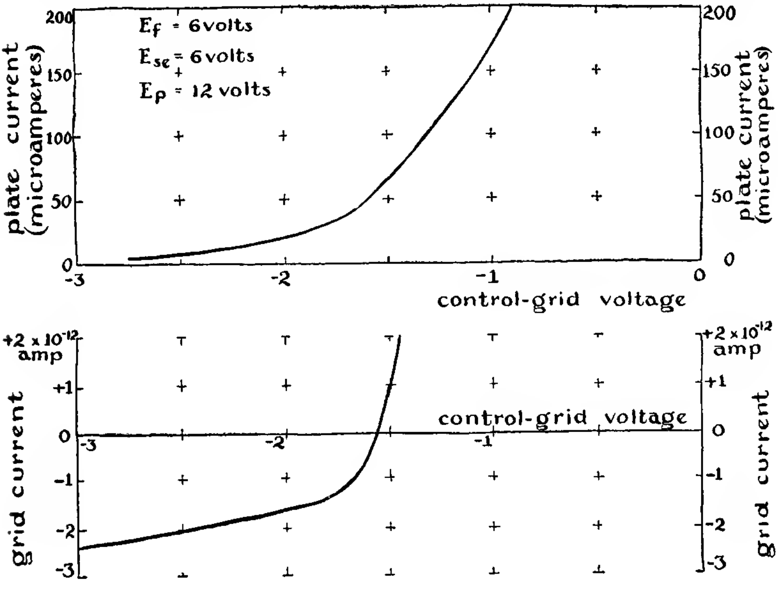

Fig. 13. Plate- and grid-current characteristics of RCA 38.

frequently by selection a tube may be found which has a grid current as low as 10^{-12} ampere. After a careful investigation Johnson found[30] that the RCA 38 pentode had good characteristics in this respect. Dunning[31] has recommended the Western Electric 259-B screen grid tube. MacDonald[32] has found the RCA 22 very satisfactory at low voltages and has given complete data on its characteristics.

[30] Johnson, E. A. and A. G., *Phys. Rev.*, *50*, 170 (1936).
Johnson, E. A., and Neitzert, C., *Rev. Sci. Instruments*, *5*, 196 (1934).
[31] Dunning, J. R., *Rev. Sci. Instruments*, *5*, 387 (1934).
[32] MacDonald, P. A., *Physics*, *7*, 265 (1936).

The grid current of a tube is often the most important characteristic in choosing a tube to amplify small currents or small voltage. The following procedure is convenient in obtaining data for plotting the grid-current curve: The plate current is plotted as a function of the grid voltage in the usual way, first with no resistance in the grid circuit and then with a high resistance in series. The horizontal difference between the two curves represents the potential drop in the resistance due to the grid current, and by dividing this voltage difference by the value of the resistor, the grid current in amperes is found. A shielded box is necessary.

Characteristic curves for the RCA 38 pentode from Johnson's data are shown in Fig. 13. This probably represents the results for a selected tube. From the slope of the lower curve it is found that the grid resistance at -2 volts is 10^{12} ohms. At equilibrium potential this is reduced to 5×10^{10} ohms.

Gabus and Pool[33] found that the RCA 954 acorn pentode can be operated in such a way as to have a very low grid current and correspondingly high input resistance. The No. 3 grid, normally used as the suppressor, is used as the control grid. Owing to the peculiar construction of the tube, this grid is very well insulated. The No. 1 grid, normally the control grid, is connected to the cathode. The No. 2 grid, normally the screen grid, is operated at a positive potential and acts as in the electrometer tube to protect the control grid from positive ions emitted by the cathode.

A particular 954 tube tested under conditions similar to those recommended by Gabus and Pool had the following characteristics: Heater voltage, 4 volts; grid No. 1 connected to cathode; grid No. 2 at $+13.5$ volts; grid No. 3 at -4 volts; plate at $+6$ volts; plate current, 60 microamperes; mutual conductance, 100 microamperes/volt; plate resistance, 35,000 ohms; amplification factor, 3.5; grid current, 4×10^{-13} ampere.

[33] Gabus, G. H., and Pool, M. L., *Rev. Sci. Instruments*, *8*, 196 (1937).

For many applications in measuring currents down to 10^{-13} ampere, any of the above-mentioned tubes will be found quite satisfactory and much less expensive than electrometer tubes.

High-gain direct-current amplifiers. Direct-coupled multistage d.c. amplifiers similar to the familiar a.c. amplifiers have been used very little because of the necessity of a separate power supply for each stage and because of difficulties with cumulative drift and instability.

Horton[34] has described an ingenious circuit in which extremely high gain is realized by utilizing one high-mu

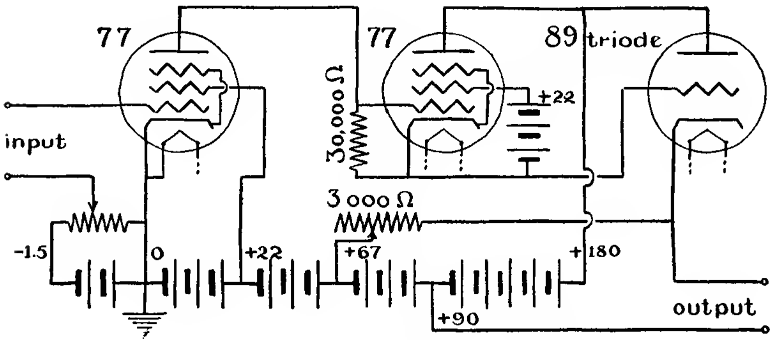

Fig. 14. Horton's high-gain d.c. amplifier.

pentode as the load resistance for another. In this way high amplification can be obtained without the very high plate supply voltage that would be necessary if a pure ohmic resistance were used for the load. The circuit is shown in Fig. 14.

All plate potentials are supplied by a 180-volt battery, and the insulation between the heater and cathode of these tubes is sufficiently good that a common heater battery may be used. The over-all mutual conductance of this three-tube amplifier is about 4.5 mhos. If the amplifier is to work into a high-impedance load, such as a cathode-ray oscillograph, the type 89 output tube may be omitted and the load con-

[34] Horton, J. W., *Frank. Inst., J.*, *216*, 749 (1933).

nected directly between the cathode of the second pentode and the 90-volt tap of the plate battery. In this case the voltage amplification is about 2500. Because of the capacity shunt through the heaters, the circuit has a poor response for high audio frequencies. In a similar circuit described by Schmitt,[35] in which separate heater batteries are used, this limitation is largely removed. Circuits of this type have found special application in the measurement of physiological potentials in which the resistance in the input circuit is low. Since the 77 tube (and similar high-gain pentodes) have a rather low grid-to-filament resistance, it is advisable to add a preliminary stage when measuring photoelectric currents. This would consist of an electrometer tube or other low-grid-current tube, operated from separate batteries. With such a combination a stable current amplification of 10^{10} is possible, and the indicating instrument may be a milliammeter.

Alternating-current amplifiers. One great advantage of an a.c. amplifier is that all the tubes of a multistage amplifier may be operated from a common power supply. The signal is transmitted from one stage to the next by means of a condenser or transformer, which, while providing insulation against steady potentials, offers a low impedance path for a.c. signals. Since only rapid variations are passed along, such an amplifier is insensitive to drifts in the plate current of any tube, and to gradual changes in the supply voltage. The characteristics of a.c. amplifiers have been treated so extensively elsewhere[36] that they will be considered only briefly here. The discussion will be limited to resistance-capacity coupling.

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[35] Schmitt, O. H. A., *Rev. Sci. Instruments*, *4*, 661 (1933).

[36] Chaffee, E. L., *Theory of Thermionic Vacuum Tubes*. New York: McGraw-Hill Book Company, 1933.

Glasgow, R. S., *Principles of Radio Engineering*. New York: McGraw-Hill Book Company, 1936.

Henney, K., *Radio Engineering Handbook*, Second Edition. New York: McGraw-Hill Book Company, 1935.

The Radio Tube Manual, issued by the RCA Manufacturing Company, Harrison, New Jersey, contains much practical information.

Fig. 15 shows a photoelectric cell and three-stage amplifier for use with modulated light intensities in the audio-frequency range. The power is supplied from the 110-volt a.c.

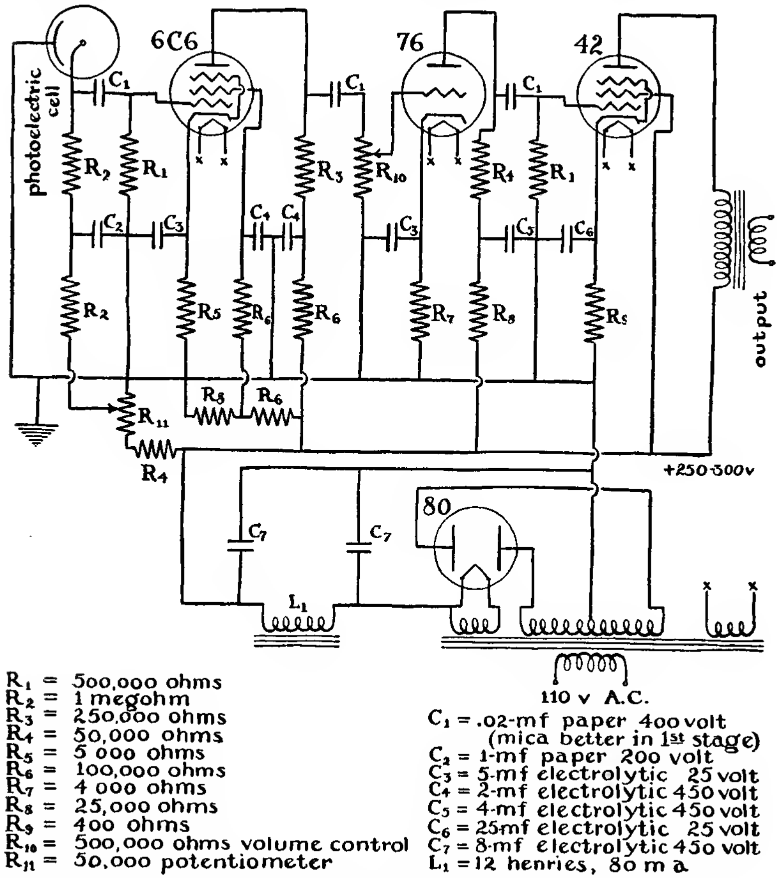

Fig. 15. Three-stage a.c. amplifier for photocurrents from a modulated or interrupted light source.

line, rectified and filtered in the usual manner to provide the necessary d.c. voltages.

In order for the coupling condensers C_1 to perform their function of transmitting the voltage variation of the plate of one tube to the grid of the next, their impedance must be small compared with the associated grid resistor R_1. The

reactance of a condenser in ohms is given by the well-known formula $X = 1/(2\pi fC)$, where f is the frequency in cycles per second and C is the capacity in farads. A simple computation shows that when $C_1 = 0.02$ microfarad, the reactance becomes equal to 500,000 ohms, the value of the grid resistor R_1, at a frequency of 16 cycles. This, then, is roughly the low-frequency cutoff of the above amplifier.

The high-frequency cutoff is determined by the tube capacities shunting the plate-load resistors and grid resistors. At high frequencies, the coupling condenser has negligible impedance, so that the coupling resistors may be considered to be in parallel. Considering first the photocell circuit, the resistors R_2 and R_1 have a resistance in parallel of 333,000 ohms. The capacity shunting this is the sum of the capacity of the photocell, the connections, and the dynamic input capacity of the first tube. The dynamic input capacity is given by the expression

$$C = C_0 + C_{gf} + [1 + \mu R_l/(R_p + R_l)]C_{gp},$$

where C_0 is the capacity of the photoelectric cell and connections, C_{gf} is the grid-to-cathode capacity of the tube, C_{gp} is the grid-to-plate capacity, μ is the amplification factor of the tube, R_p is the plate resistance of the tube, and R_l is the plate-load resistance. In a screen-grid tube, such as the 6C6, the grid-to-plate capacity is very small, and the last term is therefore unimportant. The grid-to-cathode capacity is about 6 micro-microfarads. The total capacity may be roughly 15 micro-microfarads, which has a reactance equal to 333,000 ohms at a frequency of 34,000 cycles. This is the high-frequency cutoff for the input circuit. If a gas-filled cell is used, its lower response at high frequencies must of course be taken into account.

The situation in the coupling between two stages follows the same general reasoning. In place of the capacity of the photocell there is the plate-to-cathode capacity of the tube delivering the signal to the coupling network. Also, the dynamic plate resistance of the tube is in parallel with the

resistors of the coupling network. The high-frequency cutoff may be regulated by attaching a shunting condenser to either the plate-load resistor or the grid resistor. This has been analyzed by Johnson,[37] who showed that by proper choice of coupling and shunting condensers, an amplifier may be fairly sharply tuned to a single frequency.

The necessary negative voltage for the grid of each tube is obtained by a self-bias resistor in the cathode lead. If the a.c. variations in plate current are allowed to pass through this resistor, the grid bias will be altered in such a direction as to produce a serious degenerative effect, and the amplification is much reduced. Consequently the bias resistor is shunted by a by-pass condenser, which must provide a low-impedance path for the a.c. component of the plate current. To keep the impedance less than that of the bias resistor at the lowest frequencies amplified, a rather large capacitance is sometimes required, but inexpensive low-voltage electrolytic condensers are available for the purpose.

Some care is necessary to prevent regenerative coupling of the first and last stages through the common power supply, the result of which is to produce a type of oscillation known as motorboating. The remedy is a decoupling filter of the resistance-capacity type in voltage lead to the photocell, and to the screen grid and plate of each tube except the power tubes. The principle to be followed is that the condenser in each filter unit should offer an impedance to the signal about 10 times less than its associated resistor at the lowest frequency passed by the amplifier. This is equivalent to the requirement that the time constant RC of each filter unit be 10 times longer than the time constant of the grid coupling condenser and resistor. For the amplifier shown in Fig. 15 the time constant of the coupling circuits is 0.01 second throughout. The time constant of the plate and screen-grid decoupling filters of the 6C6 tube (R_6C_4) is 0.2 second, thus more than meeting the requirement. It is worth while to have a good margin of safety in the filters for

[37] Johnson, E. A., *Physics*, 7, 130 (1936).

the photocell and first tube, which are, of course, most sensitive to feedbacks. All such filters also act to eliminate any ripple in the rectified d.c. voltage from the power pack. Shielding of the photocell and first tube is necessary to eliminate undesirable pickup.

The above-described amplifier is illustrative of the general design of a.c. amplifiers. For detecting very small light intensities, additional precautions must be taken, with special attention given to the first stage. A grid resistor of high value is used and the cell connected directly to the grid without a coupling condenser. A tube with low grid current is desirable, but an electrometer tube is ruled out because of its very low amplification factor and its sensitivity to microphonic disturbances. The RCA 38 or the Western Electric 259B operated at reduced voltages is probably the most satisfactory tube for the first stage. Careful shielding is of course necessary. Each tube with its coupling resistors and condenser should be in a separate metal compartment, with an adjacent enclosure for the associated bias resistor and decoupling filters. The tube for the output stage must be selected with special reference to its load. The next to the last tube is usually of a type intermediate between a voltage amplifier and a power amplifier. Johnson and Neitzert[38] have described an amplifier for small a.c. voltages which used RCA 38 pentodes at reduced voltages for all stages except the output. Separate plate batteries are used for each stage, but the plate current is low enough so that small units can be used. They may therefore be placed in the same compartment with the tube. Difficulties with regenerative coupling through the plate power supply are thus eliminated. Dunning,[39] in a paper on amplifiers for detecting single ionizing particles, gives many practical suggestions.

Fluctuation noises in vacuum-tube circuits. The background fluctuations of the currents in vacuum tubes which

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[38] Johnson, E. A., and Neitzert, C., *Rev. Sci. Instruments*, *5*, 196 (1934).
[39] Dunning, J. R., *Rev. Sci. Instruments*, *5*, 387 (1934).

determine the smallest signal that may be detected have long gone by the name of "noise," a term which is convenient even when there is no conversion of the currents into sound. When extraneous disturbances due to vibration, poor shielding, poor insulation, poor connections, and the like are eliminated by suitable precautions, there remain three inherent sources of noise, originating in the first tube and its input circuit:

1. Thermal noise in the grid resistor.
2. Shot effect of currents in the grid circuit.
3. Tube noise.

It is important to the laboratory worker to be able to calculate the expected noise voltage in a particular circuit, or he may erroneously attribute the noise to an extraneous disturbance and waste much time in attempting to improve something that cannot be improved, except possibly by redesigning the circuit. Pearson[40] has published a discussion of the subject and has given data on low-noise tubes made by the Western Electric Company.

The mean square voltage appearing across the grid resistance R as a result of thermal agitation of charge within it is given by

$$\overline{E_T^2} = 4kTR \int_{f_1}^{f_2} \frac{df}{1 + 4\pi^2 R^2 C^2 f^2},$$

where k is Boltzmann's constant, T is the absolute temperature, f_2 and f_1 are the upper and lower limits of the band of frequencies passed by the amplifier, and C is the dynamic input capacity of the first tube.

In case the second term in the denominator of the above integrand is small compared with unity for all frequencies between f_2 and f_1, as is required in order to avoid frequency

[40] Pearson, G. L., *Physics*, *5*, 233 (1934).
See also Johnson, E. A. and A. G., *Phys. Rev.*, *50*, 171 (1936).
For data on RCA 38 see Johnson, E. A., and Neitzert, C., *Rev. Sci. Instruments*, *5*, 196 (1934).

distortion, the expression for thermal noise becomes, for a temperature of 300°K.,[41]

$$\overline{E_T^2} = 1.64 \times 10^{-20} R(f_2 - f_1).$$

As an example, we may compute that the thermal-noise voltage across a resistance of 1 megohm connected to an amplifier which has a band width of 10,000 cycles (that is, the audio-frequency range) would be 13 microvolts.

The mean square voltage due to shot fluctuations of the grid current is

$$\overline{E_S^2} = 2eI_gR^2 \int_{f_1}^{f_2} \frac{df}{1 + 4\pi^2R^2C^2f^2},$$

where e is the electronic charge and I_g is the sum of the absolute values of the positive and negative components of the grid current.

The same equation applies for the shot effect of the photocurrent from vacuum cells. In gas-filled cells each photoelectron releases an average charge $\mu_g e$, where μ_g is the gaseous amplification factor. For rough computation $\mu_g e$ may be used as the unit of charge in the formula, but Kingsbury[42] found that actually the noise is somewhat greater than that computed on this assumption.

Tube noise cannot be less than the thermal noise in the internal plate resistance. A variety of factors serve to make it several times this theoretical minimum. The usual way of rating tubes is to give the resistance which, if placed in the grid circuit, would give the same noise voltage in the output as that produced by the tube itself. Low-noise tubes have an equivalent resistance of from 4000 ohms to 40,000 ohms. Tube noise is unimportant in amplifiers designed for amplification of photocurrents, since the resistance in the grid circuit is practically always much higher than these values.

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[41] Boltzmann's constant $k = 1.37 \times 10^{-16}$ erg/degree. At 300°K., or room temperature, $kT = 0.41 \times 10^{-13}$ erg $= 0.41 \times 10^{-20}$ joule. The latter unit is, of course, the proper one to use in connection with coulombs, volts, amperes, and farads. The electronic charge $e = 1.6 \times 10^{-19}$ coulomb.

[42] Kingsbury, B. A., *Phys. Rev.*, *38*, 1458 (1931).

When measuring very small currents with an electrometer tube, the grid resistor is made very large, or the floating-grid method is used. Under these conditions, where the circuit itself, rather than the galvanometer, determines the speed of response, the equations for thermal noise and shot noise take on a simple form. As shown by Hafstad,[43] the following relations then hold:

$$\overline{E_T^2} = \frac{kT}{C},$$

and

$$\overline{E_S^2} = \frac{eI_gR}{2C}.$$

It is to be noted that the thermal noise is independent of resistance and is therefore a very general limitation on all electrometers. If $C = 10^{-11}$ farad, a practical minimum for the grid circuit, including photocell and connections, the thermal noise for 300°K. may be calculated to be 20 microvolts. If $R = 2 \times 10^{11}$ ohms and $I_g = 10^{-15}$ ampere, the computed shot noise is 1.3 microvolt, negligible in comparison with thermal noise. The resultant uncertainty in a current measurement is 10^{-16} ampere.

However, if a resistance of 5×10^{10} ohms or less is used with a 6-second galvanometer, the galvanometer limits the speed of response, an effect equivalent to increasing the capacity. The observed noise voltage is then reduced to about 8 to 10 microvolts. A large capacity in the grid circuit would also reduce the noise voltage, but the deflection time would be increased by just enough to make the precision remain the same.

When the tube is operated with the grid at the equilibrium potential, R is the input resistance of the tube itself, about 10^{14} ohms, and I_g has two components, each of 10^{-15} ampere. The computed shot noise is then 40 microvolts. The thermal noise is of course unchanged from the previous case. With a total noise voltage of $\sqrt{40^2 + 20^2} = 45$ microvolts, the uncertainty in any measurement of charge then amounts to

[43] Hafstad, L. R., *Phys. Rev.*, *44*, 201 (1933).

4×10^{-16} coulomb, or, for a collection time of 1 minute, an uncertainty in the current of 7×10^{-18} ampere. In this case it is advantageous to have a low capacity. These are theoretical limits, but with reasonable care they may be realized in practice.

Applications of Photoelectric Cells

General remarks on photoelectric photometry. The most important laboratory use of the photoelectric cell is in photometry. Used properly, it is capable of giving results of high precision. It should be remembered, however, that very few cells have a constant sensitivity. Both the absolute sensitivity and the color response may change with time. For this reason, in careful measurements the photoelectric cell should be called upon only to make comparisons between a standard and an unknown source. Some cells are subject to fatigue when exposed to a bright light. If the linear relation between current and light intensity is to be depended on over a range of more than two- or threefold, it must be tested. The inverse-square law offers a convenient method.

If the light is to be projected on the sensitive surface by an optical system, the illuminated area should not be too small. An out-of-focus image about 1 cm in diameter is satisfactory. The light from different successive sources should cover the same area as nearly as possible. This reduces errors from local variations in sensitivity on the surface.

There are three general methods in photoelectric photometry:

1. Substitution method. The cell is exposed alternately to the standard source and to the unknown, and the relative deflections noted. This is the simplest and most direct method and is capable of giving excellent results. Of course it depends on the linearity of the cell and the current-measuring instrument.

2. Balanced-cell method. Two cells are connected in opposition, and the intensity of either the standard or the

unknown is reduced by suitable means until there is a balance. Although the method can be made very sensitive to unbalance, there is a fundamental objection to depending on the constancy of the two cells over any extended period.

3. Flicker method. The two sources shine alternately in rapid succession on the cell. The intensity of the brighter is cut down by a suitable intensity reducer until the flicker is zero. The amplifier may be of the a.c. type. A 6E5 tuning indicator ("magic eye") makes a very satisfactory detector of the minimum.[44] This is an excellent method, because the linearity of the cell and amplifier is not an issue.

When used in heterochromatic photometry, the photoelectric cell may give a judgment of relative brightness entirely different from that given by the eye, owing to the difference in spectral response. A cell with a spectral-response curve like that of the eye must be used if the visual standards of brightness are to be carried over without modification. The Westinghouse Photox cell meets this requirement very closely without the addition of any filters. The Weston Electrical Instrument Company supplies a suitable filter for use with the Photronic cell when a response curve like that of the eye is required.

For certain kinds of colorimetric measurement, the relative intensity through filters of various colors can give much useful information. Examples are the whiteness of paper[45] and the color temperature of a lamp[46] or a star.[47] However, such results are so dependent on the particular cell and particular filters used that they can be relied on only if continually checked against some kind of standard. The

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[44] Garman, R. L., *Rev. Sci. Instruments*, *8*, 327 (1937).
Waller, L. C., *RCA Review*, *1*, 111 (1937).

[45] Davis, M. N., *Paper Trade Journal*, July 4, 1935, page 36. The commercial instrument, known as a reflectance meter, is available from the General Electric Company.

[46] Campbell, N. R., and Ritchie, Dorothy, *Photoelectric Cells*, page 214. New York: Isaac Pitman and Sons, 1934.

[47] Stebbins, J., and Whitford, A. E., *Astrophys. J.*, *84*, 253 (1936); *Mt. Wilson Contr. No. 547*.

infrared transparency of practically all glass and gelatin filters mentioned on page 402 must be borne in mind.

Spectrophotometry. The first requisite in photoelectric spectrophotometry is a good monochromator. A double monochromator is to be preferred because of the greatly reduced stray light of other wave lengths than the one being used.[48]

The principal spectrophotometric measurements made in the laboratory involve spectral-radiation curves of luminous sources, spectral-transmission curves, and spectral-reflectance curves. For spectral-radiation curves, the thermocouple is preferable to the photoelectric cell because it measures energy directly. If, however, the intensity is too low for the thermocouple, a photoelectric cell may be used, provided its spectral-sensitivity curve is accurately known, so that corrections to get the energy may be applied for each wave length. The spectral-sensitivity curve for the cell can be determined by comparison with a thermocouple, using a bright light as the source for the monochromator. This is the general method for obtaining the curves shown in Fig. 1.

Spectral-transmission curves of filters, for example, may be very easily determined with a monochromator and a photoelectric cell. The intensity with the filter in and out of the beam gives the percentage transmission for each wave length. If the cell cannot be placed close enough to the slit to receive all of the exit beam, an additional lens is necessary. A minor adaptation enables absorption cells to be introduced into the beam for investigating the spectral-absorption curves of solutions.[49] Measurements of specular reflecting

[48] Preston, J. S., *Journ. Sci. Instruments*, *13*, 368 (1936), has described a simple method of eliminating errors due to stray light in a monochromator. Shutters which may occult half of the slit length are fitted to the entrance and exit slit. A reading is taken with the shutters set to let the light go through. Then one shutter is reversed, and any light coming through is stray light, for which appropriate corrections may be made.

[49] Hogness, T. R., Zscheile, F. P., and Sidwell, A. E., *J. Phys. Chem.*, *41*, 379 (1937).

Zscheile, F. P., Hogness, T. R., and Young, J. F., *J. Phys. Chem.*, *38*, 1 (1934).

power may be carried out in the same way, except that it will, of course, be necessary to move the photocell when shifting from the direct to the reflected beam.

For determinations of diffuse reflectance it is customary to illuminate the object at 45° incidence and observe along a line normal to the surface. The reflectance is measured relative to that of some standard material, such as magnesium carbonate. The fluorescence of certain materials causes difficulty, which can be eliminated only by having the reflection occur before the light beam passes through the monochromator.

All of the above-mentioned methods of spectrophotometry involve the linear response of the photocell and the current-measuring instrument. In practical cases this is not likely to cause appreciable error, but in precision work the linearity must be investigated. Mention should be made of the Hardy automatic recording spectrophotometer,[50] which works on the flicker principle and is thus independent of the cell and amplifier characteristics and variations in light intensity. This instrument is adaptable to many kinds of measurements and gives very accurate results. It is manufactured commercially by the General Electric Company.

Densitometers. In photographic photometry it is necessary to have some means of measuring the density of the photographic deposit. The photoelectric cell has found wide use as the light-sensitive unit of objective densitometers. Since photographic photometry consists of interpolation between standards whose intensity ratio is known, spectral sensitivity and exact linear response are not crucial matters.

For sensitometry of photographic materials, when an area several millimeters square is of uniform density, good results can be obtained by a very simple arrangement without any optical system at all. An automobile headlight is mounted

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[50] Hardy, A. C., *J. O. S. A.*, *18*, 96 (1928), *25*, 305 (1935). An instrument working on a similar principle is described by Sharp, C. H., and Eckweiler, H. J., *J. O. S. A.*, *23*, 246 (1933).

12 to 18 inches above a flat opaque screen with a rectangular aperture of the desired size cut in it. A photovoltaic cell is mounted directly behind the aperture and connected to a galvanometer. The plate is best laid on the aperture emulsion side down to reduce scattering effects. Miss Mohler and Miss Taylor[51] have described a reflection densitometer almost equally simple and easy to construct. Difficulties with stray light, and the effect of scattering in the emulsion will, however, be reduced if a simple projection system is introduced.

For many problems it is desired to know the density on a very small area of the plate—hence the term *microphotometer* for densitometers which are designed for such

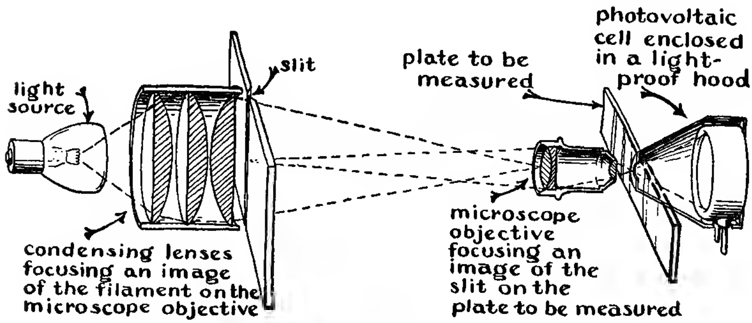

Fig. 16. Optical system of Lange's microphotometer.

applications. Lange[52] and Milligan[53] have described microphotometers using photovoltaic cells. The optical system of the Lange instrument is shown in Fig. 16. The condensing lens forms an image of the lamp filament in the principal plane of the microscope objective, which is adjusted to give a sharp image of the slit in the plane of the emulsion. The projected image of the slit may be made as narrow as 0.01 mm. The instrument is capable of giving rather high resolution.

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[51] Mohler, Nora M., and Taylor, Delia Ann, *J. O. S. A.*, *26*, 386 (1936).
[52] Lange, B., *Zeits. f. techn. Physik*, *13*, 600 (1932).
[53] Milligan, W. O., *Rev. Sci. Instruments*, *4*, 496 (1933).

The optical design and other features of microphotometers have been reviewed by Harrison.[54] To eliminate errors caused by scattered light, it is customary to use at least two slits in high-resolution instruments. In order to obtain sufficient sensitivity with reasonable speed of response, it is necessary to use an emission-type cell and amplifier. For the amplifier an RCA 38 pentode, connected as in Fig. 5, is satisfactory.[55] Suitable operating conditions and circuit constants are as follows: Heater, 6 volts from storage battery. Control grid, -1.5 volts; screen grid, $+6$ volts; plate, $+12$ volts; all from small radio batteries. Plate current, 60 microamperes. Mutual conductance, 150 microamperes/volt. Grid resistor, 10^8 to 10^9 ohms. Galvanometer, 5×10^{-8} ampere/mm. A cesium oxide vacuum photocell is recommended.

Measurements of the transmission of solutions as a function of depth and concentration can also be made advantageously by photoelectric methods. Many procedures for chemical analysis which formerly used visual methods are now carried out with increased precision by employing a photoelectric cell.[56]

The light absorption of a solution is a logarithmic function of the concentration. Over a certain range the density of a photographic plate is a logarithmic function of the intensity. It would therefore be convenient to have an amplifier with a logarithmic response in order to make a direct-reading densitometer. Hunt[57] found that a remote cutoff tube such as the type 78 can be made to have an accurately logarithmic response over a voltage range of about tenfold. By using three tubes in cascade, he was able to extend this range to over a thousandfold. This arrangement is for alternating-

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[54] Harrison, G. R., *J. O. S. A.* and *Rev. Sci. Instruments*, *19*, 267 (1929); *J. O. S. A.*, *24*, 59 (1934).

[55] Kron, G. E., private communication.

[56] Withrow, R. B., Shrewsbury, C. L., and Krayhill, H. L., *Indust. & Engin. Chem.* (*Analytical Edition*), *8*, 214 (1936).

Strafford, N., *Analyst*, *61*, 170 (1936).

[57] Hunt, F. W., *Rev. Sci. Instruments*, *4*, 672 (1933). See also Ballantine, S., *Electronics*, *1*, 472 (1931).

current voltages only. Müller and Kinney[58] have applied this principle to measuring the concentration of solutions. They report that the open circuit e.m.f. of a Weston Photronic cell is also a logarithmic function of intensity.

Amplification of small galvanometer deflections. The ultimate sensitivity of a moving-coil galvanometer is set by the Brownian movement. Because of the limitations of the optical system it is difficult to realize this limit in a galvanometer with a reasonably short period. Moll and Burger[59] described a thermo-relay in which a rotation of the coil of

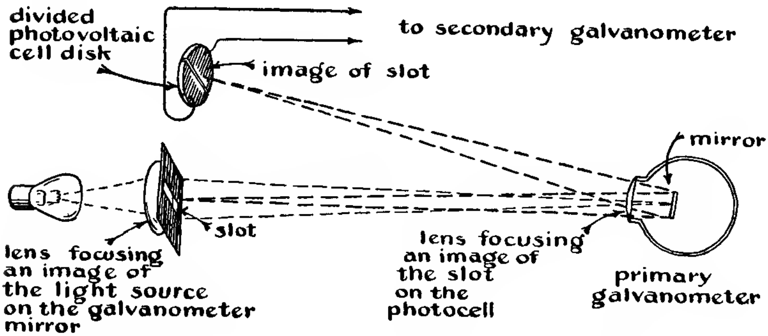


Fig. 17. Amplification of small galvanometer deflections.

only a few seconds of arc was amplified and read on a second galvanometer. More recently, amplification schemes using photoelectric cells[60] have come into use, with some improvement in the speed of response.

The simplest method of amplification involves a balanced photovoltaic-cell arrangement. The sensitive disk of a Weston Photronic cell is removed from the case. This may be done by unscrewing the back, warming gently, if necessary, to soften the pitch seal. The conducting layer on the

[58] Müller, R. H., and Kinney, G. F., *J. O. S. A.*, *25*, 342 (1935).
[59] Moll, W. J. H., and Burger, H. C., *Phil. Mag.*, *50*, 6211 (1925).
[60] Jones, R. V., *Journ. Sci. Instruments*, *11*, 302 (1934).
Moss, E. B., *Journ. Sci. Instruments*, *12*, 141 (1935). This is a general review of the subject.
See also Taylor, A. H., *Rev. Sci. Instruments*, *8*, 124 (1937).

top surface is divided into two parts by scratching a line along a diameter of the disk with a sharp instrument. Any loose particles must be brushed away. If this process is carried out properly, the two halves of the top conducting layer will be insulated from each other. Fig. 17 shows the optical arrangements. An automobile headlight bulb is focused on the mirror of the primary galvanometer by a simple lens, in the plane of which is a rectangular slot. The galvanometer lens forms an image of the illuminated slot on the divided disk of the photovoltaic cell. The two halves of the top conducting layer are connected to the secondary galvanometer, which indicates the difference in the illumination on the two sides of the center line. A distance of 1 or 2 feet between the photocell and the primary galvanometer is sufficient. The secondary galvanometer may be placed wherever it is convenient.

A current amplification of 200 is easily obtained with such an arrangement, which is sufficient to make the Brownian motion quite noticeable. Another application would be to couple two short-period, low-sensitivity galvanometers by such a device to form a high-sensitivity combination with rapid response. The over-all linearity is, of course, open to suspicion and must be tested.

Thyratrons. The introduction of a gas into a hot-cathode tube greatly increases the power it can handle, owing to the neutralization of space charge by the positive ions formed. However, the grid-control characteristic is quite different from that of a high-vacuum tube. With the grid sufficiently negative, the tube is nonconducting. At a certain critical grid potential, whose value depends on the plate voltage, the discharge starts, and the tube is said to "fire." The grid then loses control of the plate current because of a sheath of positive ions around it. The discharge can be stopped only by removing the plate voltage. The voltage drop in the tube is practically independent of current and amounts to about 15 volts. The current must be limited by resistance in the external circuit to a safe value.

The name *thyratron*[61] was first applied to these tubes only by the General Electric Company, but is coming into general use. Other terms sometimes used are *gaseous triode* and *grid-controlled rectifier*. The Westinghouse Lamp Company and the RCA Manufacturing Company also make tubes of this type. The gases used are argon and mercury vapor. Mercury-vapor tubes have the disadvantage, which is, however, usually not serious, that the characteristics are a function of the ambient temperature. Argon tubes are not subject to this variation, but are limited in their power-handling ability. The General Electric FG-81, the largest argon-filled tube, is rated at 0.5 ampere maximum average plate current and 180 volts maximum plate voltage.

In most applications gaseous triodes are used with an alternating plate voltage. During the negative half of the cycle the grid regains control. The output is then a pulsating direct current. Tubes may be used in pairs if full-wave operation is desired.

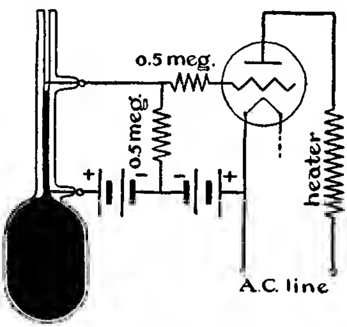


Fig. 18. Use of thyratron as a relay in a mercury-controlled thermostat.

The simplest application is as a relay. As compared to a mechanical relay, the gaseous triode requires much less power to operate, is faster and quieter, and has no contacts to pit, wear, or stick. Fig. 18 shows a gaseous triode used as the relay in a thermostat controlled by a mercury thermometer. A load of 2 kilowatts may be switched on and off with a current at the mercury contact of a few microamperes. The mercury is thus protected from contamination due to sparking.

This particular application is merely illustrative. The control may be exercised by a photoelectric cell, and the load

[61] For many details about characteristics and uses, see Hull, A. W., *Gen. El. Rev.*, *32*, 213, 390 (1929); *Physics*, *4*, 66 (1933).

may be a light, a motor, or a magnet. If response to even smaller grid power is required, a four-electrode tube known as a shield-grid thyratron is available.[62]

Continuous variation of the average plate current between zero and full value may be obtained by a phase-shift circuit, shown in Fig. 19. The phase of the alternating grid voltage is varied by the relative values of C and R. If R is very large, the grid voltage is 180° out of phase with the plate voltage, and the tube is always nonconducting. If R is zero or very small, the grid voltage is in phase with the plate voltage, and the tube fires at the beginning of each positive half-cycle and carries the maximum current. At an intermediate value, the grid voltage will reach the critical potential at some time during the positive half-cycle, and the tube conducts for the remainder of the half-cycle. A smooth and fairly linear variation of the average current is thus possible. The resistance R may be a vacuum tube or a photoelectric cell.

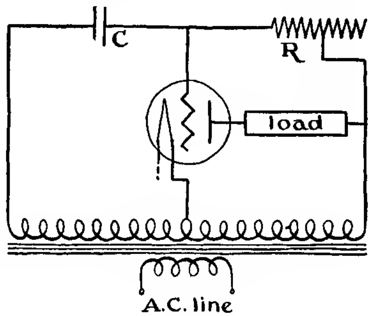


Fig. 19. Phase-shift circuit for control of thyratron.

In Fig. 20 is shown a phase-shift circuit for maintaining a constant temperature in a furnace.[63] In a test, the temperature of a furnace at approximately 880°C. was held constant within 0.06°C. The temperature is measured by a thermocouple. (A resistance thermometer would do as well.) The potentiometer is set to balance at the desired constant temperature. An automobile headlight bulb is imaged on the galvanometer mirror by the lens L_1. The galvanometer lens L_2 forms an image of L_1 on a **V**-shaped slot in front of the photocell. The amount of light reaching the cell (which should be of the gas-filled type) determines the current

[62] Livingston, O. W., and Maser, H. T., *Electronics*, April, 1934.
[63] Zabel, R. M., and Hancox, R. R., *Rev. Sci. Instruments*, *5*, 28 (1934).

through the thyratron and thus regulates the furnace temperature. R_1 is in parallel with the regulator circuit and carries most of the heater current, thus making it possible to use a smaller tube. R_2 limits the current through the tube to its rated maximum value. C may be a 200 micro-microfarad variable condenser.

This arrangement is an example of a type of control mechanism that will be found generally useful in the laboratory.

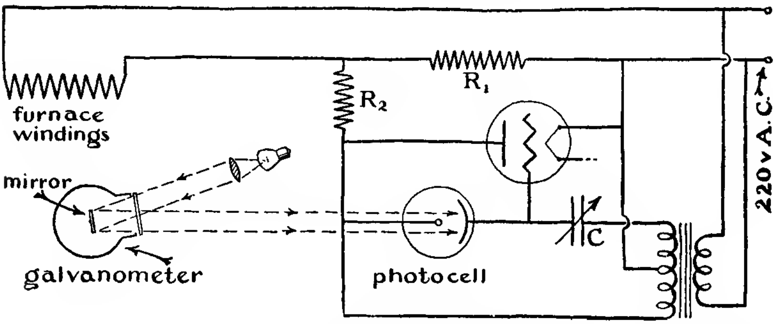


Fig. 20. Constant temperature regulator using a photocell in a phase-shift circuit.

It differs from the simple on-and-off control provided by relays in that the correcting influence approaches zero gradually as the error diminishes, and "hunting" is thereby eliminated. The same principle is applicable to devices for maintaining constant speed, constant current, or constant voltage. With two lights and two photocells, it may be used to control a motor which will balance a bridge or a scale, or perform any other "centering" operation.[64]

[64] For further applications see Henney, K., *Electron Tubes in Industry*, Second Edition. New York: McGraw-Hill Book Company, 1937.

CHAPTER XI

Photography in the Laboratory[1]

IN this chapter we will treat of photography and the photographic procedures used in making and recording observations in experimental science and especially in recording spectra.

Comparison of the sensitivities of the eye with the photographic emulsion. The relative visibilities of the various

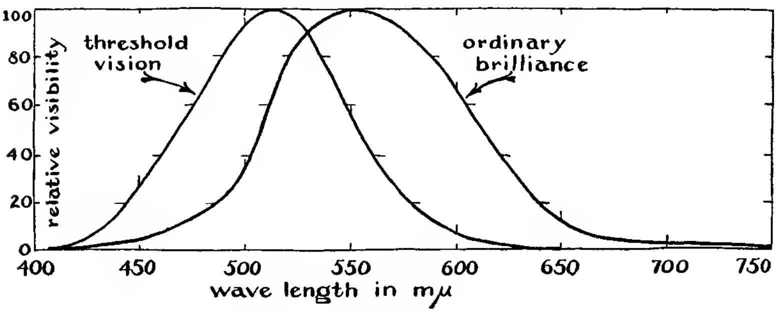


Fig. 1.

colors of the spectrum are shown in Fig. 1. To illustrate the differences of response to various wave lengths between the eye and the photographic plate, these visibility curves are to be compared with the sensitivity curves for ordinary, orthochromatic, and panchromatic emulsions that are shown in the top section of Fig. 2.

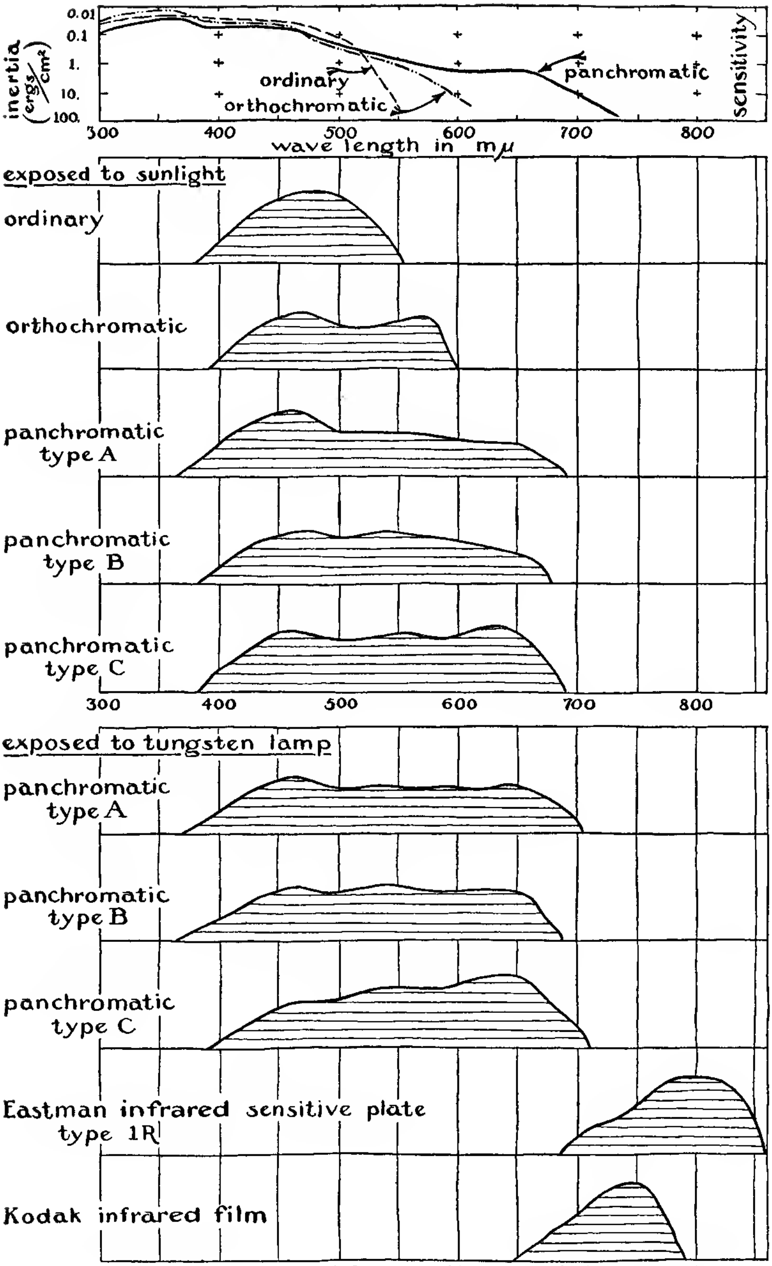
[1] I wish to acknowledge the use of material from the following sources for the preparation of this chapter:

Elementary Photographic Chemistry. Rochester: Eastman Kodak Company, 1931.

Fowle, F. E., *Smithsonian Physical Tables.* Washington: The Smithsonian Institution, 1934.

Hardy, A. C., and Perrin, F. H., *The Principles of Optics* (chapter on photography). New York: McGraw-Hill Book Company, 1932.

Neblette, C. B., *Photography.* New York: D. Van Nostrand Company, 1930.



inertia (ergs/cm²)
0.01
0.1
1.
10.
100.
sensitivity
ordinary
orthochromatic
panchromatic
300
400
500
600
700
800
wave length in mμ
exposed to sunlight
ordinary
orthochromatic
panchromatic type A
panchromatic type B
panchromatic type C
300
400
500
600
700
800
exposed to tungsten lamp
panchromatic type A
panchromatic type B
panchromatic type C
Eastman infrared sensitive plate type 1R
Kodak infrared film
300
400
500
600
700
800

Fig. 2.

Wedge spectrograms are illustrated in the lower sections of Fig. 2. These spectrograms were taken using sunlight and the light of a tungsten lamp as the light source. The height of the shaded areas indicates the sensitivity of the emulsion.

Owing to the emission characteristics of these light sources and the opacity of the lenses used for violet and ultraviolet light, the wedge spectrograms exhibit maxima at about 4700 Å, whereas, actually, the sensitivities of the emulsions, as indicated by the curves at the top of Fig. 2, show the maxima to be in the ultraviolet. However, the wedge spectrograms do give an indication of the performance of different emulsions in the camera.

Table I illustrates the relative sensitivities of the eye and the photographic plate to a line-shaped light source on a dark field. This table, together with the appearance of a spectrum line, may be used to determine the approximate exposure time for a spectrum plate.

TABLE I

Color of Linear Image of Light on Dark Background Just Visible at a Glance	Time Required to Register the Line Photographically on a Panchromatic Plate
Violet	1 minute
Blue (4500 Å)	5 minutes
Green (5200Å)	30 hours
Red hydrogen	17 minutes
Extreme red	1 minute

The material for this table appeared in the *Scientific American* a few years ago.

Hurter and Driffield curves. The characteristics of photographic films and plates are simply represented by Hurter and Driffield curves[2] (designated hereafter as H and

[2] Hurter, F., and Driffield, V. C., *Jour. Soc. Chem. Ind.*, *9*, 455 (1890). Ferguson, W. B., *The Photographic Researches of Ferdinand Hurter and Vero C. Driffield.* Royal Photographic Society, 1920.

D curves). An H and D curve is shown in Fig. 3. This curve represents the relationship between photographic response and the exposure to white light which is required to produce this response. The response, measured by the

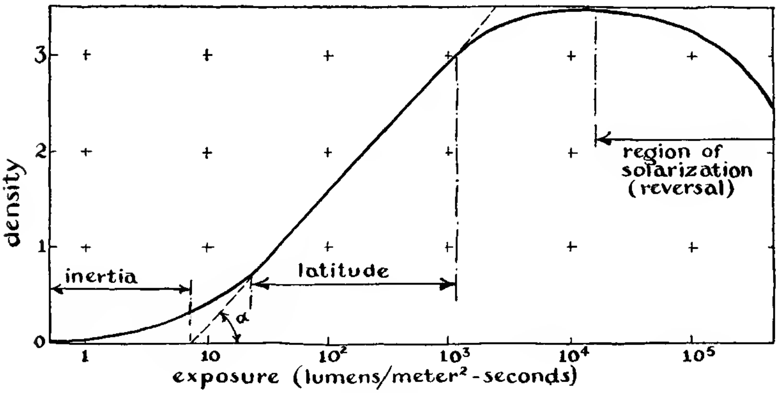


Fig. 3.

photographic density, Δ, is plotted as ordinate against the logarithm of the exposure, Σ, as abscissa. Δ is defined by the equation

$$\Delta = \log_{10} \frac{1}{T}, \tag{1}$$

in which T is the transmission of the film or plate in question.

The shape of the H and D curve depends upon the character of the emulsion, and also, if colored light is used, upon the wave length or color characteristics of the light used for exposure. Actual photographic materials may exhibit a curve differing considerably from the one shown in Fig. 3. For example, the curve does not always exhibit a definite straight segment in which Δ is proportional to the logarithm of exposure. The curve of Fig. 3 is somewhat idealized, but it represents the general character of the relationship between Δ and log Σ.

The exposure range represented by the straight segment is, by definition, the latitude of the emulsion. Table II gives the latitude of typical emulsions, from which we see that fast

emulsions have the greatest latitude and lantern slides and process emulsions the least, the variation of latitude in these emulsions being eightfold. In Table II the latitude is expressed as the ratio of the exposure at the upper end of the straight segment to the exposure at the lower end.

TABLE II

LATITUDE OF PHOTOGRAPHIC EMULSIONS

Photographic Material	Latitude (ratio of exposure at limits of the straight segment of the Δ-log Σ curve for development to γ_∞)
Motion-picture film:	
Extra fast and normal	200
Panchromatic	300
Positive	50
Commercial:	
Ordinary	75
Orthochromatic	75
Panchromatic	75
Process plates	25
Lantern-slide plates	25

Smithsonian Tables, page 342 (1936).

The contrast of an emulsion, γ, is, by definition, the slope of the straight segment of the H and D curve. If this segment makes an angle α with the log Σ axis,

$$\gamma = \tan \alpha. \tag{2}$$

The contrast varies with development time but tends to approach a limit as the development time is increased. This limiting value, γ_∞, allows comparisons to be made between the contrast characteristics of various types of emulsions. Values of γ_∞ for different emulsions are given in Table III. It will be noted that positive films, lantern slides, and process emulsions exhibit the most contrast, while fast emulsions exhibit less contrast.

The curve shown in Fig. 4, the so-called Weber-Feckner curve, illustrates the variation of the subjective response of

the eye to field brightness. In several respects it is like an H and D curve.

TABLE III

RELATIVE CONTRAST OF PHOTOGRAPHIC EMULSIONS

Material	γ_∞
Super-speed motion-picture film	1.4
Par-speed motion-picture film	1.6
Motion-picture positive film	2.7
Commercial orthochromatic	2.2
Commercial panchromatic	2.2
Ordinary commercial	2.2
Process plates	3.0
Lantern-slide plates	3.2

Smithsonian Tables, page 342 (1934).

The Weber-Feckner curve employs the logarithm of field brightness as abscissa, and this curve exhibits an inflection point near which it is closely approximated by a straight line. The proportionality of Δ for an H and D curve, as well as the subjective response of the eye for a Weber-Feckner curve, to the logarithm of the "amount of light"

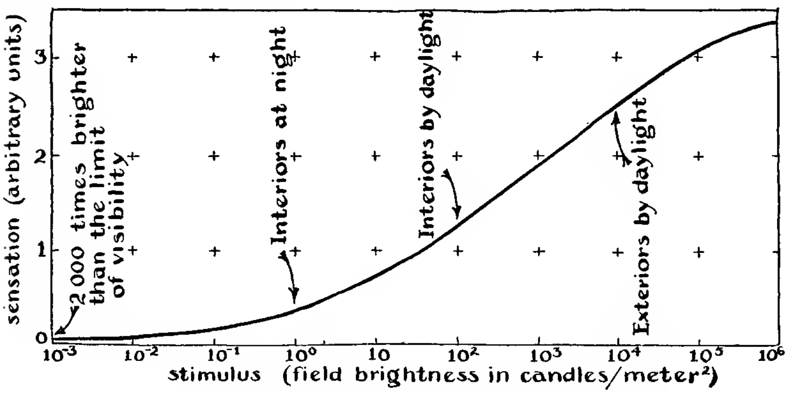


Fig. 4. After Hardy and Perrin. (See footnote 1.)

indicates why photographs look natural. It also indicates why the ordinary fading type of exposure meter works as well as it does.

The contrast sensitivity of the eye is related to the slope of the Weber-Feckner curve, and it is such that one can just distinguish a difference in brightness of about 2 per cent between contiguous uniformly illuminated fields. It is of interest to point out that the contrast of a field can be enhanced by photography by about ninefold—threefold by the photographic process of taking the primary photograph and threefold by the printing process. Accordingly, it is possible to see detail in a photograph which is invisible to the unaided eye.

The H and D speed of a photographic material S is defined as 34 divided by the inertia expressed in lumen seconds per square meter.

$$S = \frac{34}{i}. \tag{3}$$

The inertia, illustrated in Fig. 3, is the exposure represented by the intersection of the extrapolated straight segment of the H and D curve with the line $\Delta = 0$.

Reciprocity law. The photophysical and photochemical effects produced in a plate by the exposure Σ are measured by the density Δ. Equal effective exposures Σ' produce equal densities under the condition of controlled development. To a degree of approximation sufficient for most applications (precise photometric photography excepted) the effective exposure is equal to the product of the illumination on the plate, I, multiplied by the time of exposure t. Thus,

$$\Sigma' = \Sigma = I \cdot t. \tag{4}$$

This is the so-called Bunsen and Roscoe reciprocity law.

For greater accuracy it is necessary to replace Eq. 4 by more complicated expressions. One of them, Schwarzschild's,[3] takes into account the difference in effectiveness when the emulsion is exposed a short time to a bright light and when it is exposed a long time to a dim light. Schwarzschild's relation is given below:

$$\Sigma' = I \cdot t^p. \tag{5}$$

[3] Schwarzschild, K., *Astrophys. J.*, *11*, 89 (1900).

We may take the behavior of motion-picture positive film as an example to show to what extent the Bunsen and Roscoe law fails. For the range of illumination intensities from 1 to 33,000 it is found that p varies from 0.68 to 1.00, the maximum intensity being 131 lumens/m^2 and the exposure time varying between 18.2 hours and 2.5×10^{-4} second.

Another factor to be considered in predicting the photographic response to a given exposure is whether the illumination is intermittent or continuous. The photographic emulsion is incapable of responding as completely to an exposure impressed as short flashes of light as to an equal uniform exposure. Also, everything else being equal, the photographic response is diminished if the time interval between flashes increases.[4]

The resolving power. The resolving power of a photographic plate may be measured by the number of lines per millimeter which can be distinctly photographed. The

TABLE IV

RESOLVING POWER OF PHOTOGRAPHIC EMULSIONS

Material	Optimal Resolving Power (lines/mm)
Motion-picture film:	
Extra fast	50
Normal	55
Panchromatic	50
Positive	80
Ordinary commercial	65
Commercial orthochromatic	65
Commercial panchromatic	60
Process ordinary	90
Process panchromatic	75
Lantern slide	100

Smithsonian Tables, page 343 (1934).

[4] For a more complete treatment of the failure of the reciprocity law, see Jones, L. A., "Measurements of Radiant Energy with Photographic Materials," *Measurement of Radiant Energy.* New York: McGraw-Hill Book Company, 1937.

resolving power varies by a factor of about 2 for the ordinary photographic materials. For lantern-slide plates the resolving power is about 100/mm, but for fast motion-picture film it is only half as great, or about 50/mm. (See Table IV.)

Light sources. Photographs are frequently taken with achromatic lenses. The flint components of these lenses will not transmit light at wave lengths shorter than about 3300 Å. The transmission curve for a moving-picture projection lens containing a flint component is shown in Fig. 5. In practice a

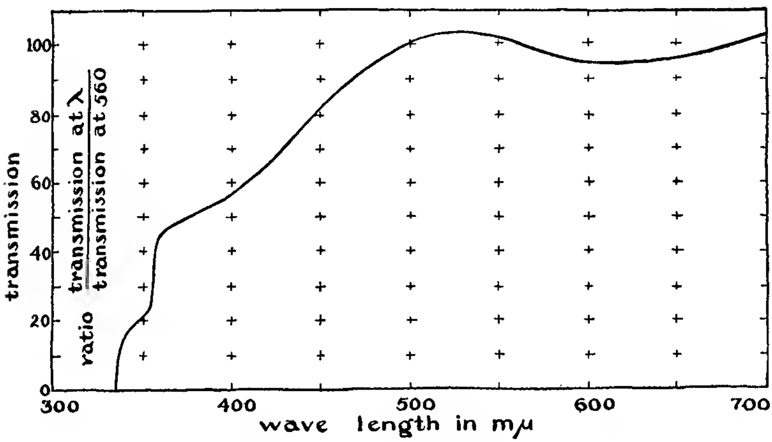


Fig. 5. Transmission of a motion-picture projection lens.

wave-length limit of 3800 Å is often low enough to define the behavior of a photographic material when account is taken of this opacity of the lenses used and also when the ultraviolet emission of ordinary light sources is considered.

The spectral energy distributions in the light of various tungsten lamps used for photography are given in Fig. 6. It will be noted that the emission is weak at short wave lengths. The spectral distribution of sunlight is also given there. As a matter of convenience for comparing the curves, the intensities are all set equal to 1 at 5600 Å.

The color temperatures of various sources are given in Table V. Of these, the photoflash lamp is of special interest.

It is of value for inside photography, since it eliminates the danger and smoke of flashlight powder and the expense of other suitable sources such as the electric arc. This lamp is an ordinary pear-shaped bulb filled with aluminum foil and oxygen. The foil is ignited by a "fuse," or small chemical

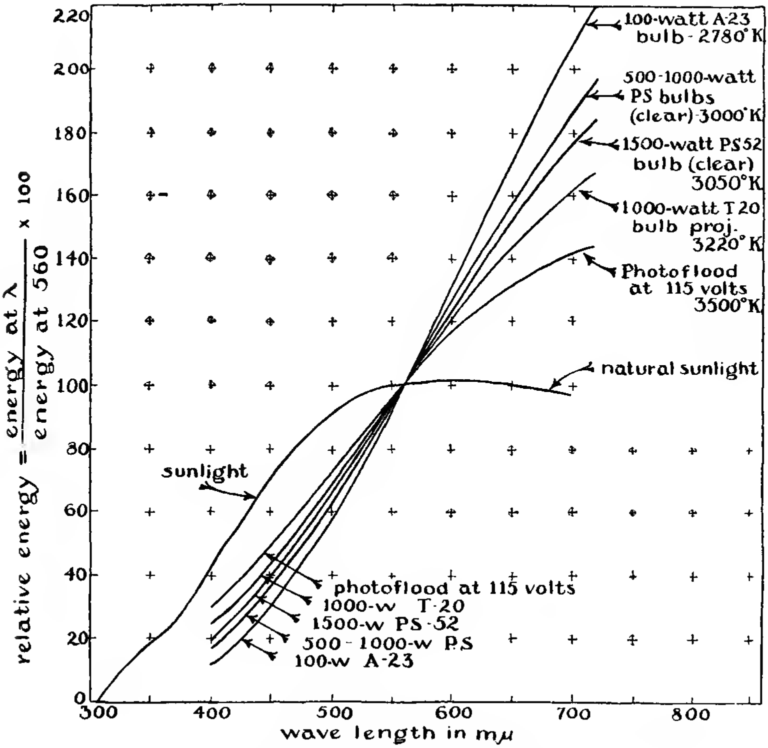


Fig. 6. Data for tungsten lamps supplied by the General Electric Company, Nela Park, Cleveland, Ohio.

flash, set off by applying 3 volts or more to the screw socket of the base. When two or more of the lamps are close together, it is necessary to apply voltage to the base of only one of them and the others will go off "sympathetically." The light generated is 22 to 180 thousand lumen seconds, depending upon the size of the lamp. This light is emitted in an interval of time varying from $\frac{1}{50}$ to $\frac{1}{25}$ second. Half

the total radiation is emitted in an interval of $\frac{1}{100}$ to $\frac{1}{200}$ second. When the voltage is applied to the base, the lag between the time when the fuse is operated and the instant of maximum illumination is about $\frac{1}{55}$ second, or, if the lamps are "sympathetically" flashed, the lag between the first and second flash is about $\frac{1}{77}$ second. The maximum light intensity from a bulb of the size of an ordinary 75-watt tungsten lamp is 4 to 5×10^6 lumens.

TABLE V

COLOR TEMPERATURES OF VARIOUS SOURCES (TEMPERATURE OF A BLACK BODY GIVING THE SAME COLOR OF LIGHT)

Source	Color Temperature (°K.)
Sun	5400
Sky	25,000
Nernst filament	2400
Ordinary tungsten lamp	2780 to 3000
Photoflood lamp	3500
Flash powder	3800
Ordinary cored carbon arc	4000
Photoflash lamp	>5000

Filters. For photographing with the microscope, in order to prevent excessive heating, it is necessary to use a water filter to absorb out heat radiation from the light emitted from the carbon arc. Frequently, copper chloride or sulphate is added to the water in the cell to increase its infrared absorption. These additions do not materially attenuate the transmission of the cell for yellow, green, and blue light.

On the other hand, when it is required to transmit the infrared and absorb the visible rays, one can use a cell containing a solution of iodine in carbon disulphide.

Color filters for use in photography can be made up from solutions, or they may be purchased in the form of colored gelatin films, either unmounted or mounted between glass plates. The unmounted films are the cheapest, and they

generally serve as well as those that are mounted. Transmissions for some of the Wratten gelatin filters[5] used in photography are given in Fig. 7.

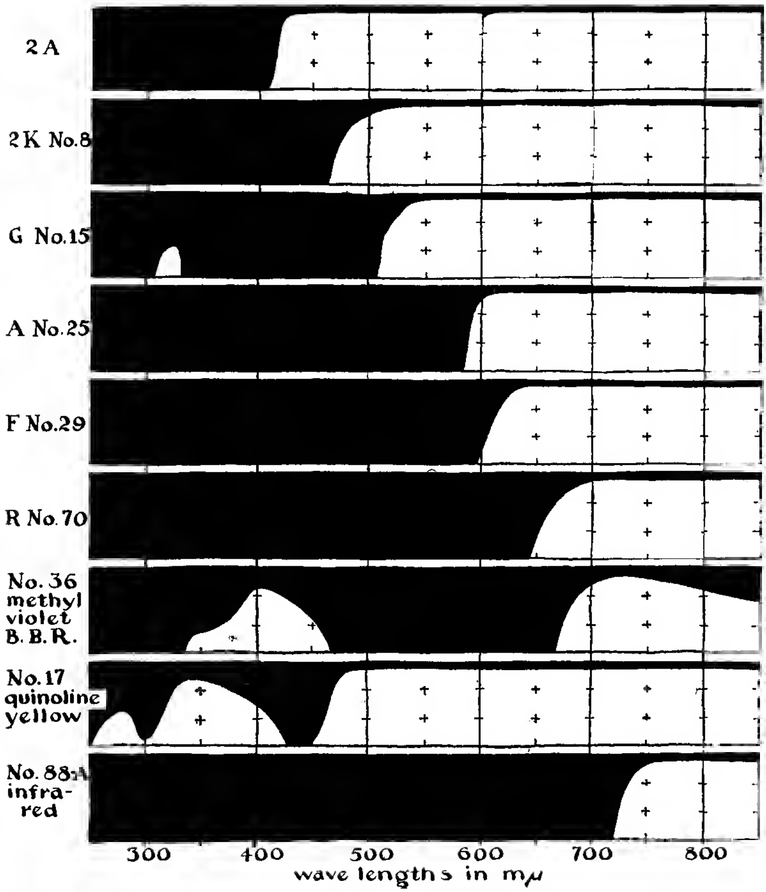


Fig. 7. Wratten filters.

There are several preliminary procedures to be carried out before the photographic emulsion is ready for exposure. These include focusing, sensitizing, annealing, and judging the correct exposure time to be given.

[5] Wratten filters are handled commercially by the Eastman Kodak Company, Rochester, New York. See the book *Wratten Light Filters*, published by that company, price 50 cents.

Focusing. Focusing may be accomplished by taking several pictures at different positions of the plate holder or lens. Sometimes, however, this procedure is not the most convenient one. For example, in focusing the plate in an astronomical telescope, a "knife-edge" test may be used for determining the focus. This is accomplished by means of an attachment which is substituted for the plate holder and which is constructed so that the knife edge comes to the same plane as that occupied by the emulsion when the plate holder is in position. The camera as a whole is then adjusted until the cutting of the knife into the star image results in a uniform decrease in the intensity of the rays that come from different parts of the mirror. After this, when the plate holder is replaced, the emulsion will be in focus.

In a spectrograph a strip of paper across the center of the telescope or collimating lens and parallel to the slit facilitates the determination of the focus. When the photographic plate or viewing glass is not in exact focus, a double image of the spectrum lines is obtained.

A uranium glass plate may be used for focusing ultraviolet light. The fluorescence of this glass is easily visible for the stronger ultraviolet lines in the mercury spectrum.

Sensitizing. Ordinary photographic plates respond to wave lengths from 2400 Å to 5500 Å, with the maximum sensitivity at about 3600 Å. Sensitization is required beyond these limits. Although the photographically active grains themselves are sensitive for all wave lengths shorter than those of the visible spectrum, the emulsion becomes less sensitive at wave lengths below 2800 Å, because of opacity of the gelatin in the emulsion. Although absorption by the gelatin is weak at 2800 Å, it increases at shorter wave lengths, especially below 2400 Å, until the gelatin is completely opaque at 2000 Å. Schumann made the first photographic plates which were sensitive at wave lengths below 2000 Å by using a very thin emulsion almost free from the opaque gelatin. Not only are the Schumann plates useful for photographing in the ultraviolet spectrum, but they also serve in

those applications in which the lateral motion in the emulsion is to be rigorously avoided or in which lateral scattering of light must be minimized.

The sensitivity of ordinary photographic plates may be increased at wave lengths below 2400 Å by coating them with a fluorescent substance such as oil. The sensitivity can be

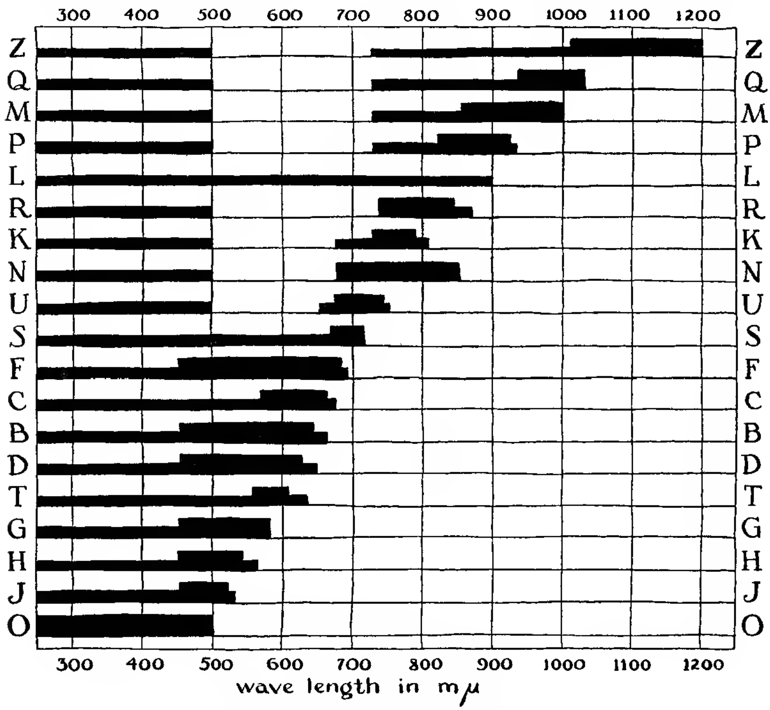


Fig. 8. Diagrammatic representation of the sensitivity of spectrum plates available from the Eastman Kodak Company.

increased as much as four hundredfold. A few drops of Nujol or some other oil are spread over the surface with a cotton pad. After exposure and before development the oil is washed away with acetone. Harrison has studied the sensitometry of oiled plates, and he states that they may be used for photographic photometry.[6]

[6] Harrison, G. R., *J. O. S. A.*, *11*, 113 (1925).

Plates are sensitized for the red and infrared with dyes. The diagram shown in Fig. 8 represents the characteristics of spectrum plates which are available commercially.[7]

Plates may be hypersensitized by bathing them in either an ammonia or a borax bath. The formulas for these baths are given below.

AMMONIA FORMULA

Bath Temperature: 10° to 12°C.

Ammonia (0.91 sp. gr.)	2 cc
Alcohol	275 cc
Distilled water	725 cc

Immerse 2 minutes. Do not rinse. Dry as quickly as possible after removing surface liquid.

BORAX FORMULA

Bath Temperature: 12°C.

Sodium chloride	0.5 g
Borax	2 to 3 g
Distilled water	1 liter

Immerse 2 to 6 minutes. Do not rinse. Soak in methyl alcohol 1 minute. Dry as quickly as possible after removing surface fluid.

The hypersensitizing action of the baths is relatively greater for the slower emulsions. Treatment with the ammonia bath can be expected to produce 100 to 400 per cent increase of speed for the visible spectrum, while infrared plates exhibit an even greater increase in speed of 500 to 2500 per cent. Hypersensitized plates fog rapidly at room temperature, so that they should be used as soon as possible after they are dry. However, they can be kept for a few days in an icebox. After they are removed from the icebox, they should be warmed to room temperature to avoid the condensation of moisture when they are loaded in the camera. The borax treatment is said to be best for Agfa plates, and the ammonia bath for Eastman plates.

Photographic plates may also be hypersensitized by a 36-hour exposure to mercury vapor at ordinary temperatures.[8]

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[7] Mees, C. E. K., *J. O. S. A.*, *25*, 80 (1935).

[8] See Dersch, F., and Duerr, H., *J. Soc. of Motion Picture Engineers*, *28*, 178 (1937). The effect of exposure to the mercury vapor is said to be more marked after exposure than before.

We see from the H and D curve given in Fig. 3 that a certain exposure is required before the linear part of the curve is reached. R. W. Wood introduced the procedure of pre-exposing the plate to a uniform illumination.[9] Although this allows the attainment of increased density with a given exposure, it does so with attendant loss of contrast. To avoid the Herschel effect, one should use, for the pre-exposure, a wave length that is redder than the light that is being photographed. Other investigators who have experimented with pre-exposure, notably Whipple in connection with stellar spectroscopy and Norman with photographic photometry, may be consulted for further details.[10]

Gelatin shifts. Annealing of the unexposed emulsion may be required for photographic plates such as spectrum plates and astrographic plates on which it is necessary to make measurements of the highest precision. Gelatin shifts may occur on account of strains, in the supporting gelatin layer, which are relieved by the developing process. Accordingly, the position of silver in the developed image may not coincide exactly with the position of the same silver in the latent image. Cooksey and Cooksey observed shifts of the latent image as great as 9μ.[11] These authors found, however, that such shifts are reduced about fourfold by the following annealing procedure: The plate is wet in a neutral solution, washed, and then dried by absorbing the water from the gelatin with alcohol.

More frequently gelatin shifts arise on account of improper drying. Large shifts occur around spots where the gelatin does not dry uniformly. To avoid these shifts it is recommended that, after fixing, the plate be dried in an alcohol bath, in which the removal of water from the gelatin is much more uniform than it is when the drying is effected by evaporation. It is advisable not to use a spectrum plate nearer the edge than 1 cm, since the gelatin shifts are greatest near the edge.

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[9] Wood, R. W., *Astrophys. J.*, *27*, 379 (1908).

[10] Norman, D., *J. O. S. A.*, *26*, 407 (1936).

Whipple, F. L., *Lick Observat.*, *Bull.*, No. 442.

[11] Cooksey, D., and Cooksey, C. D., *Phys. Rev.*, *36*, 80 (1930).

Because of their shrinking and expanding, photographic films are unsuitable for precise photography. The effect of changes in the film can, in a large part, be allowed for if coördinate lines (with a reseau) or, in the case of a spectrum, comparison spectral lines, are impressed on the plate at the time of exposure.

Exposure. Photographic films and plates are ordinarily exposed to get proper contrast. As long as the range of

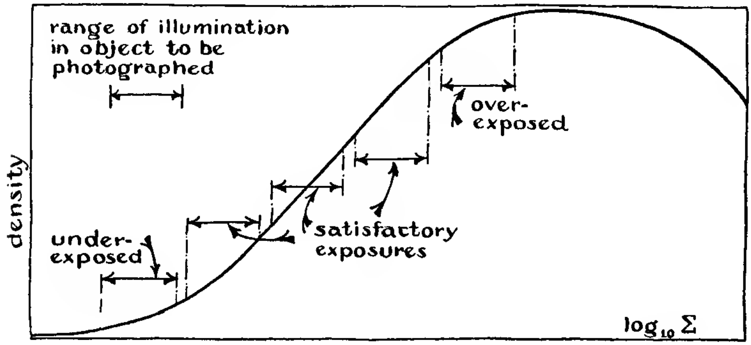

Fig. 9.

illumination in the object to be photographed is small compared to the latitude of the emulsion, the exposure can vary between wide limits. As a result, the density may vary, but as long as the exposure falls within these limits, the contrast obtained will be the same. This is illustrated in Fig. 9.

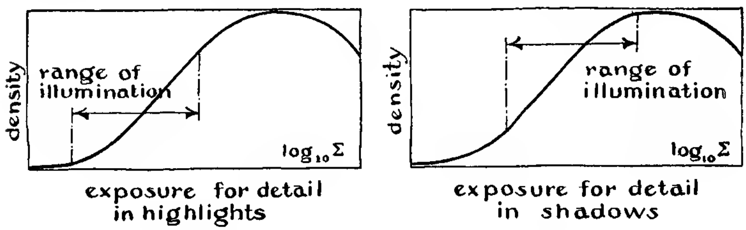

Fig. 10.

If the range of illumination is greater than the latitude as shown in Fig. 10, the exposure should be adjusted to get proper contrast where it is desired. For example, if the

highlights are important, the emulsion should be underexposed for the shadows, and if the shadows are important, it should be overexposed for the highlights.

In photography, particularly artistic photography, one may wish to render detail in both highlights and shadows even where the range of illumination may involve a ratio as great as 3000 to 6000 between the maximum and minimum exposure. Although no film exhibits such a latitude (see Table II), this range of exposure can often be managed by overexposure and underdevelopment. That this procedure yields less contrast and greater latitude is indicated by Fig. 11, in which it will be noted that the projection of the straight segment of the Δ-log Σ curve representing 32 minutes development embraces an exposure range only half as broad as that embraced by the curve for 2 minutes development. Furthermore, the regions of exposure beyond the straight segment do not deviate so much from a straight line for the case of 2 minutes development as for the case of 32 minutes development.

On the other hand, when a subject is "flat," such as a sand dune, the professional photographer takes his largest camera and gives the plate a short exposure and then a long development to get maximum contrast. The photographer uses the large camera inasmuch as a long development time produces graininess, which becomes conspicuous on enlargement.

The correct exposure may be determined by means of an exposure meter and the tables and scales supplied with it. The photronic-cell type of exposure meter is especially useful, but it has the undesirable feature that its response represents an average of the illumination received over a large solid angle. When the exposure is to be adjusted to the illumination of some small object which is much brighter or darker than its surroundings, it is necessary to put the photronic meter close enough to the object so that it substantially fills the field of view of the meter.

Tables and calculators like the Wellcome calculator are

useful for roughly estimating the exposure.[12] To increase the chance of getting correct exposure, one should take auxiliary pictures at one half and twice the exposure predicted by the calculator. Such a practice is especially feasible with miniature cameras, for which the cost of film is small.

The speed of a given photographic material varies with the color characteristics of the illumination, depending upon whether it is sunlight, arc light, or light from a tungsten lamp. The exposure can be accurately estimated only after taking account of a color factor as well as the intensity of illumination. The success of an estimate depends largely upon the experience of the photographer.

When unfamiliar conditions of illumination are encountered, the correct exposure is usually determined by trial. A

TABLE VI

EXPOSURE CHARACTERISTICS OF DIFFERENT PHOTOGRAPHIC EMULSIONS FOR VARIOUS LIGHT SOURCES

Material	Sun	Crater of High-Intensity Arc	Ordinary Arc 4000°K.	Tungsten		
				3200° K.	3000° K.	2800° K.
Super-speed motion-picture film.......	72,000	50,000	16,200	1570	800	400
Par-speed motion-picture film.......	36,000	25,000	8100	780	400	200
Motion-picture positive film..........	3600	2500	820	76	39	20
Bromide paper......	180	125	41	3.8	2	1

Hardy, Arthur C., *J. O. S. A.*, *14*, 515 (1927).

Exposure required to give a perceptible image on various photographic materials. The values given in the table are $B/\sigma \times 10^{-6}$, where B is the intrinsic illumination in candles per square centimeter and σ is the exposure to give a perceptible deposit in lumen seconds per square centimeter.

[12] This calculator may be obtained from Burroughs Wellcome and Company, 9 East 41st Street, New York City.

succession of trial plates is taken, the exposure of each varying by a factor of 2, 3, or 5.

Table VI is useful for estimating exposure. This table gives the ratio of the intrinsic illumination B to the exposure σ required for the various light sources to yield a perceptible deposit on the photographic material indicated in the left-hand column of the table.[13] B is in candles per square centimeter and σ in lumen seconds per square centimeter, so that the ratio B/σ has the dimensions $1/(\text{solid angle} \times \text{seconds})$. If the product of the quantity B/σ multiplied by the solid angle of the illumination cone on the film and as well by the exposure time is equal to or greater than unity, a perceptible image will result.

The values of B/σ are useful for designing recording instruments to determine the maximum velocity v at which the recording spot can traverse the film and yet produce a readable trace. Let us consider a recording system, say one to record galvanometer deflections. First, we must determine the exposure time and solid angle of illumination. If the width of the spot is d, then d/v gives the exposure time for those areas of the photographic material which have been traversed by the spot. The solid angle of the illumination is determined as follows:

Case I. For the case in which a galvanometer mirror of area A acts as field stop and the light is focused on the film by a spherical lens immediately in front of the galvanometer, the solid angle is A/f_1^2, when f_1 is the distance of the film from the spherical lens.

Case II. For the case in which an astigmatic optical system is used, wherein the width of the galvanometer mirror, w, determines the lateral field stop, and the stop on the cylindrical mirror is h, the solid angle is

$$\frac{w}{f_1} \times \frac{h}{f_2}.$$

Here, f_1 is the distance of the film from a spherical (or

[13] Hardy, A. C., *J. O. S. A.*, *14*, 505 (1927).

cylindrical) lens in front of the galvanometer mirror, and f_2 is the distance of the film from the cylindrical lens near the film. (See Fig. 47, Chapter IX.)

Accordingly, for Case I the condition for obtaining a record is

$$\frac{B}{\sigma} \cdot \frac{A}{f_1^2} \cdot \frac{d}{v} \geq 1$$

and for Case II, the condition is

$$\frac{B}{\sigma} \cdot \frac{w}{f_1} \cdot \frac{h}{f_2} \cdot \frac{d}{v} \geq 1.$$

Development. The aim of development is to render in photographic blackening the variations in illumination registered as the latent image in the photographic emulsion. Sometimes, as in a snapshot, one may wish the rendition to be "normal," so that the positive print will seem to represent faithfully the original scene. On the other hand, one may wish to repress or enhance contrast by changes in the development procedure.

The development process is not completely understood. Grains of silver bromide which have been exposed to light are reduced to metallic silver by the developer, while those not so exposed are not easily reduced. The developer will, however, finally reduce unexposed grains. The reduction of unexposed grains produces a general fogging of the plate, called chemical fog.

The progress of development with time is illustrated in Fig. 11. The various H and D curves shown here represent a series of exposures, on five different plates. Each of the plates was developed for a different length of time, namely, 2, 4, 8, 16, and 32 minutes. It is characteristic of development that the contrast increases with the time of development. At first the increase is rapid; for example, in 2 minutes the contrast of the material represented in Fig. 11 increased from 0.32 at t = 2 minutes to 0.58 at t = 4 minutes, an increase of 0.26. Later, the rate of increase falls

off; for example, in 16 minutes the contrast increased by only 0.3 from 1.4 at t = 16 minutes to 1.7 at t = 32 minutes. The contrast approaches a limit γ_∞ for very long development. We have referred to this quantity before and tabulated it for representative photographic materials. (See Table III.) An interesting geometrical feature of the H and

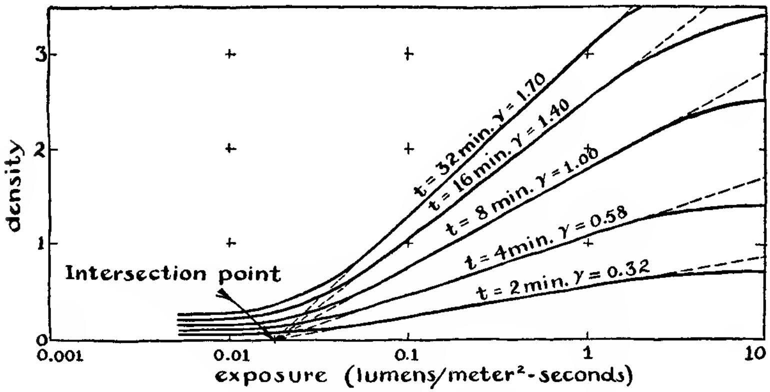

Fig. 11. After Hardy and Perrin. (See footnote 1.)

D curves shown in Fig. 11 is that their extrapolated straight segments have a common intersection point with the line $\Delta = 0$.

Developers are composed usually of four constituents: (1) The reducing agent—metol (elon), pyrogallol, glycin, amidol, or hydroquinone; (2) the alkali accelerator—caustic soda, sodium carbonate, or borax; (3) the preservative—usually sodium sulphite or bisulphite; (4) the restraining agent—potassium bromide.

Most developing solutions will not develop at all unless they are alkaline, and all of them act more rapidly in proportion to the concentration of the alkaline accelerator.

Oxygen dissolved by alkaline solutions may oxidize the reducing agent. In the case of pyrogallol this oxidation is particularly objectionable, for it yields a yellow-colored product which stains the emulsion. Oxidation can be avoided if the preservative sodium sulphite is added to the

developer. This substance rather than the pyrogallol reacts with the dissolved oxygen, forming sodium sulphate.

The characteristic effect of the restraining agent, potassium bromide, is to depress the intersection point, referred to above, below the line $\Delta = 0$ and at the same time bromide suppresses development in the low exposure range. A small amount of bromide which is not enough to depress the intersection point much will, however, exert a selective enough restraining effect on the development to inhibit the formation of undesired chemical fog, without having any sensible effect on the development of the desired image.

There are two general procedures for development: time and temperature, or tank development; and factorial, or tray development. By the first method, the film is immersed in a tank of developer for a prescribed length of time. This time is determined by the nature of the film, by the degree of contrast desired, and also by the type, concentration, age, and temperature of the developer.

By the second method, the progress of the development may be watched. Panchromatic emulsions are desensitized to make this possible. The time at which the development is to be terminated is either determined by inspection or calculated from the time required for the image first to appear.

Time and temperature development. The rate of development, as in any chemical reaction, increases rapidly with temperature. It is a practical rule in chemistry (although not a very rigid one) that a reaction rate increases by a factor of 2 for each 10° rise in temperature. This rule applies to development; for example, with pyro-soda developer this factor is 1.5. Time-temperature tables are available for the various developers. However, to get proper contrast and to prevent excessive graininess and fogging, it is advisable to carry on development at the temperature specified by the formula. For developers containing both metol and hydroquinone it is particularly important to develop at the temperature specified in the formula in order to obtain the

proper proportionate effect of each reducer. Metol has a low temperature coefficient, while hydroquinone has a high one. As a matter of fact, some operators take advantage of this difference and use hydroquinone-metol developers warm to obtain one grade of contrast and cold to obtain another. This procedure is not recommended, but it does illustrate the point in question.

The common developers may be made up from the stable stock solutions listed in Table VII. These solutions are combined in the proportions given in Table VIII at the time they are needed, a procedure which is at the same time both economical and convenient.[14]

TABLE VII

STOCK SOLUTIONS FOR MAKING VARIOUS DEVELOPING BATHS

A		*B*	
Metol or elon	2.5 g	Hydroquinone	6.7 g
Anhydrous Na_2SO_3	18 g	Anhydrous Na_2SO_3	12 g
Watcr to make	200 cc	Water to make	200 cc
C		*D*	
Anhydrous Na_2CO_3	400 g	KBr	10 g
Water to make	2 liters	Water to make	100 cc
E		*F*	
Anhydrous Na_2SO_3	400 g	Borax	10 g
Water to make	2 liters	Water to make	250 cc

Solutions *C*, *D*, *E*, and *F* are very stable and may be prepared and kept in large stock bottles. Solutions *A* and *B* are less stable, and therefore should be stocked in small bottles to avoid an excessive amount of air over the solutions. Use distilled water for making the solutions. Dissolve chemicals for Solutions *A* and *B* in the order listed.

[14] I am indebted to Dr. John McMorris for suggesting these tables.

TABLE VIII

PROPORTIONS FOR COMPOUNDING DEVELOPING BATHS FROM THE STOCK SOLUTIONS OF TABLE VII

Developer	Solutions					
	A	*B*	*C*	*D*	*E*	*F*
Contrast Plate: D-28	34	25	24.5	3.5	0	0
Process tank or tray: D-11	8	27	12.5	5	26	0
Fine grain: D-76	16	15	0	0	38.5	5
D-72 (Chloride paper)	25	37.5	34	2	0	0
D-72 (Bromide paper)	10	15	13.5	0.8	0	0

The quantities are parts, by volume. The developer is compounded in the order *A* to *E* in the expressed proportions and then diluted to 100 parts, by volume. For the first three formulas, develop at 65°F. (18°C.). For papers, develop at 70°F. (21°C.). See *Elementary Photographic Chemistry* for further details.

Developers such as Sease 3 give fine grain, but they require extra exposure. So-called compromise developers, such as Edwal 12, yield fine grain, and at the same time they do not require excessive exposure. Compromise developers were first made for use with miniature cameras. Recently, however, they have had some application in astronomy.[15] Formulas for both the Sease 3 and Edwal 12 developers are given below.[16]

SEASE 3

(for twice normal exposure)

Sodium sulphite (anhydrous)	90 g
Paraphenylene diamine	10 g
Glycin	6 g
Distilled water	1 liter

Developing time: 30 minutes at 65°F. (18°C.).

With careful regulation of exposure and developing temperature, negatives are produced which can be enlarged to 50 diameters and beyond.

[15] Morgan, W. W., *Astrophys. J.*, *83*, 254 (1936).
[16] The Edwal Laboratories, 732 Federal Street, Chicago, Illinois.

EDWAL 12

(for normal exposures)

Sodium sulphite (anhydrous)	90 g
Paraphenylene diamine	10 g
Glycin	5 g
Metol	6 g
Water	1 liter

Developing time: 12 to 18 minutes at 65° F. (18° C.).

This developer keeps well and will give a finer grain when it is a month or two old than when it is fresh. The fineness of the grain produced also increases after it has been used the first time.

For obtaining fine grain and absence of reticulation, it has been recommended that the temperatures of the developer, rinse water, fixer, and final wash water all be equal to within $\pm$ 2°F.

Over-all density is not important for films or plates that are to be printed. The recommended procedure is to disregard density in development. One develops for the desired contrast rather than for a specified average density.

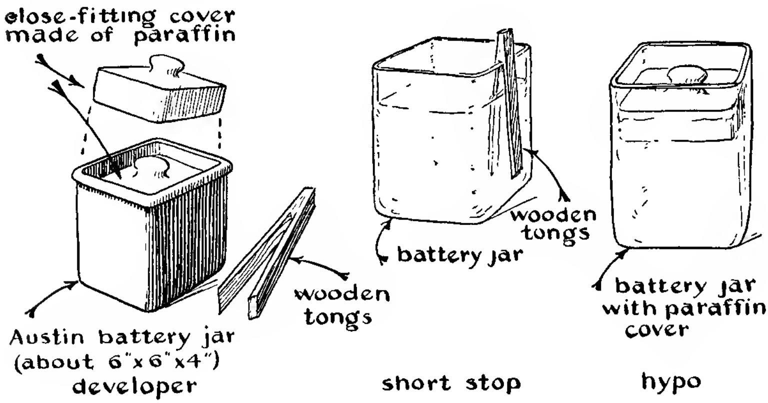

Fig. 12.

Fig. 12 shows equipment for developing. The paraffin covers shown protect the solutions from oxidation and evaporation when they are not in use.

Tray development. When the emulsion is immersed in the developer, the time for the first appearance of the image is

proportional to the time for its full development. Accordingly, the time for first appearance of the image may be used to determine the proper time of development. This is helpful when the concentrations of the chemicals in the developing bath are different from those specified in the formula. In such a case one would not otherwise know how long to develop. The ratio of the time required for proper development to the time required for the image to appear is a characteristic of the developer and is called the Watkins factor. This factor varies with temperature for two-reducer developers like metol-hydroquinone; but for others it can be used to correct for high or low temperature as well as for deviations in chemical composition of the developer. Watkins factors for several developers are given in Table IX.

TABLE IX

WATKINS FACTORS

Developer	Watkins Factor		
	Soft Contrast	Normal Contrast	Strong Contrast
Pyro-soda	4	6	7
Glycin	8	10	12
Hydroquinone	6	9	10
Metol	10	12	15
Metol-hydroquinone	10	12	15

The Wellcome Handbook.

When one is working for high contrast under conditions which allow observation of the progress of development, the rule is to develop in D-28 or D-11 until the image appears on the back of the emulsion. This rule applies particularly to the production of good lantern-slide and spectrum plates.

Aerial fog is often encountered in tray development. It is caused when the plates, wet with developer, are exposed to the air. "Seeding" the developing solution with 5 per cent

of old developer, which is rich in bromide, has a negative catalytic action on this fogging. The metals tin, copper, zinc, and their alloys often produce fog and stain on the emulsions when they come in contact with the developers in which the emulsions are treated. For this reason, development in brass and soldered metal trays is to be avoided.

Plates for photometric work should be developed in a tray in a deep solution and brushed continuously with a camel's-hair brush. This accelerates convection near the emulsion and results in more even development. Regions in which the film has a strong exposure give off bromide during development, and unless this is removed by brushing, it restrains further development both at the place it is generated and at adjacent regions in the emulsion.

Plates and films should be held by their edges, ends, and corners, and the fingers should not be allowed to come in contact with the important areas of the emulsion. In some cases the use of rubber gloves is indicated. Important plates should be rinsed in water before development.

Desensitizing. Panchromatic emulsions must ordinarily be developed in the dark. However, the Luppo-Cramer discovery of the desensitizing action of phenosafranine on the unexposed silver grains allows illumination of panchromatic emulsions with a green safelight during the latter stages of development. The selective desensitizing action of this dye on unexposed silver bromide grains is quite mysterious; the development proceeds after the light is turned on as it would in darkness. The plate is separately immersed in the desensitizing solution for 2 minutes in darkness before development (1 part of a stock solution, of $\frac{1}{2}$ g phenosafranine in 1 liter distilled water, to 10 parts water). Pinakryptol green added to the developer may be employed as desensitizing agent. The stock solution is a 1:500 solution of the dye in distilled water—2 to 3 cc of this solution is added to each 100 cc of developer.[17]

[17] Neblette, C. B., *Photography*, page 298. New York: D. Van Nostrand Company, 1930.

Fixing. After proper development and washing, it is often adequate to fix the plate or film by immersion in a 20 per cent solution of sodium thiosulphate (hypo) crystals. The hypo dissolves out undeveloped silver bromide grains.

The plate usually carries some developer into the fixing solution and if the fixing solution contains no preservative, the transposed developer will be gradually oxidized and form products which may stain the film. Accordingly, to avoid this effect, fixing solutions are usually compounded with the preservative sodium sulphite added to the hypo. A weak acid is also added to neutralize alkali brought in on the plates. The acid has the further function of stopping development. Fixing solutions may also contain hardeners, such as potassium or chrome alum. These hardeners "tan" the gelatin, prevent excessive swelling and softening of the gelatin, and make it less "soluble" in water.

A short stop is used to stop development and to conserve the acid in the hypo. Plates are immersed in the short stop solution after the development and before fixing.

SHORT STOP

Water	1000 cc
Acetic acid, 28 per cent	48 cc

This solution is to be made up fresh each time it is used. It does its work in about 5 minutes.

The Eastman bath F-5, made up according to the formula given below, is a good one, and it is recommended for fixing.

EASTMAN ACID HARDENING FIXING BATH F-5

Water at 52°C	600 cc
Hypo crystals	240 g
Sodium sulphite (anhydrous)	15 g
Acetic, 28 per cent	47 cc
Boric acid crystals	7.5 g
Potassium alum	15 g
Water to make	1 liter

The chemicals listed in the formula are to be dissolved in the order given. For best results one should use only fresh fixing solution. It is best to fix plates for twice the time

required to clear the gelatin of unreduced silver salts. With acid in the fixing bath the room lights may be turned on a few seconds after the plates are immersed.

Ordinary gelatin melts in water at about 40°C. Normal hardening increases the melting temperature to between 55° and 77°C. However, for extreme hardening, Formalin is used. In less than a minute a 5 per cent solution of this chemical renders the gelatin film insoluble, even in boiling water. Formalin does not work in acid solutions. The following formula is recommended by the Eastman Company:

FORMALIN HARDENER

40 per cent formaldehyde solution	10 cc
Sodium carbonate (anhydrous)	5 g
Water to make	1000 cc

Washing and drying. It is necessary to remove the fixing solution from the emulsion by thorough washing. Table X gives the minimum time required for washing various emulsions when the surface of the emulsion is held under a tap so that it is continually in contact with fresh water. But when these materials are washed in a tray without agitation, the diffusion of the fixing chemicals through the emulsion proceeds more slowly. As a working rule, the washing time should not be less than the time required to wash the emulsion under the tap plus the time required to wash the tray. The latter time is determined by measuring the time required

TABLE X

WASHING TIME FOR VARIOUS EMULSIONS

Emulsion	Time (minutes)
Lantern-slide plates	3
High-speed negative emulsions	7
Chloride papers	15 to 20
Bromide papers	20 to 60

From *Elementary Photographic Chemistry.*

to clear the tray of a strongly colored ink solution. The rate of washing is roughly independent of temperature, and it is also unaffected by hardening if the hardened emulsion has not been dried. A final rinsing with distilled water is recommended. Fig. 13 illustrates methods for washing plates, films, and papers.

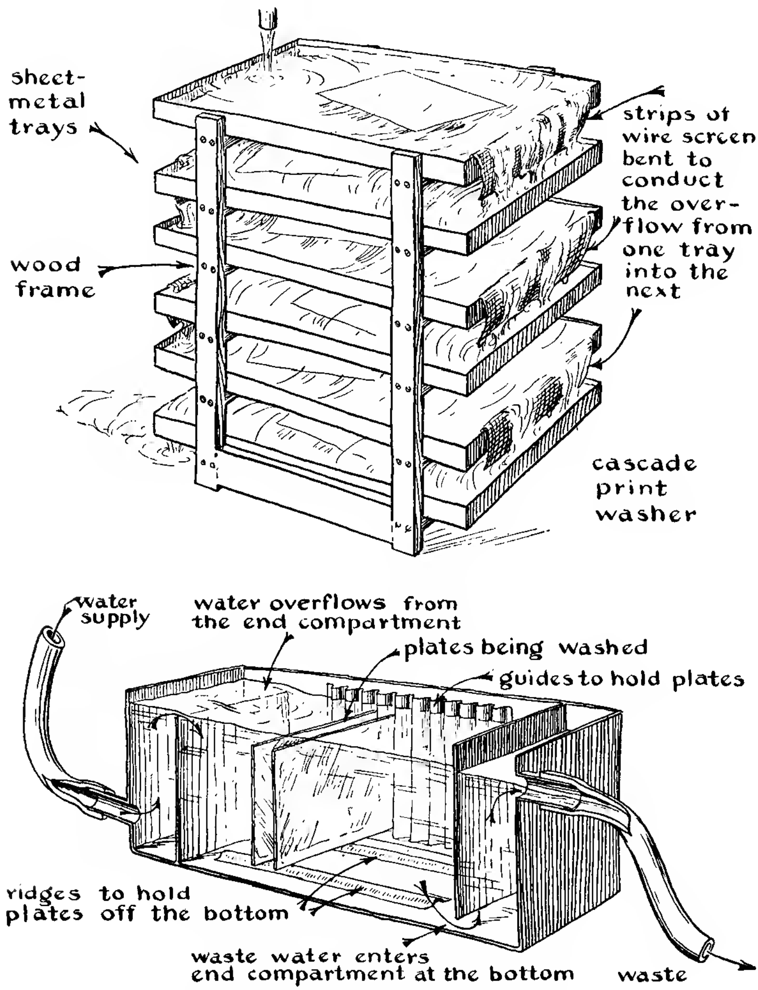

Fig. 13. Washing of plates and papers.

Plates and films are usually dried in a current of dust-free air. The air can be slightly warmed, since the heat of evaporation will keep the emulsion cool. Apparatus suitable for this is illustrated in Fig. 14. Fig. 15 shows a drying cabinet for films.

The dry emulsion on negatives is about 0.0005 of an inch thick and normally contains 8 to 16 per cent moisture. It is five to seven times as thick as this when it is wet. The swelling of gelatin is characterized by the fact that it is anisotropic, being perpendicular to the glass. Even when

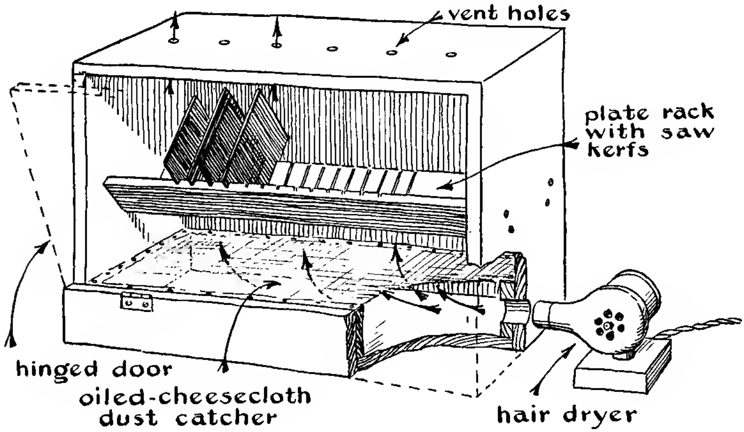

Fig. 14. Drying cabinet.

gelatin is free from the lateral restraint, offered by the glass support, the swelling is principally in one direction. However, when the film dries unevenly, silver grains are shifted laterally. The edge of a plate dries first, and the shifts produced are appreciable as far back from the edge as 1 cm. Drops of water (tears) or the excessive water held around a dust particle will produce lateral shifts of the emulsion. To avoid these shifts, the emulsion may be wiped with a damp cotton pad, a chamois skin, or better yet, a cellulose sponge. An automobile windshield wiper can be used to remove tears from plates and films.

The plate can be dried in 80 per cent alcohol when maxi-

mum accuracy to the edge of the plate is desired and also when distortions such as those caused by dust specks and tears are to be avoided. The alcohol is then evaporated from the emulsion by a current of moist air. If the alcohol or the air is too dry, the water in the gelatin will be reduced below the normal amount, and this subnormal water content

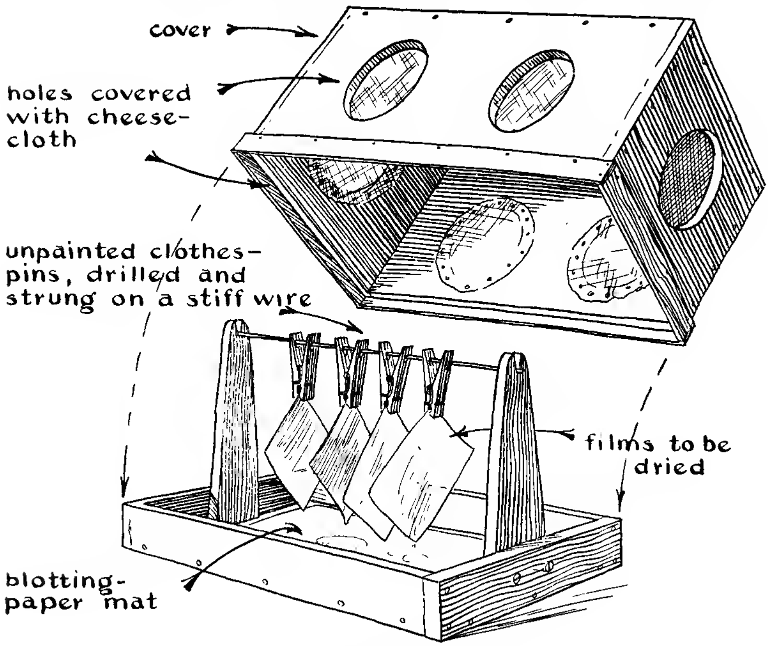

Fig. 15. Drying cabinet for films.

turns the gelatin white. The water content of the gelatin can be raised to remove the milky appearance by breathing on the emulsion once or twice.

Printing and enlarging papers. Negatives are printed on so-called printing-out papers, gaslight papers, or bromide papers. Printing-out papers are exposed to light through the negative until the image develops. The chloride (gaslight) papers are exposed and then developed with chemical developers. They are relatively insensitive and can be manipulated in a lighted room. Bromide papers must be

managed in darkness or under a safelight, in the same manner as ordinary unsensitized photographic plates are managed. The chloride and bromide papers are the most important, and we will discuss them here.

The reflectivity-density Δ for papers is defined as follows:

$$\Delta = \log_{10} \frac{1}{R}. \tag{6}$$

R is the diffuse reflectivity of the paper. H and D curves for chloride contact and bromide enlarging papers, plotting Δ as ordinates against the logarithm of exposure as abscissa,

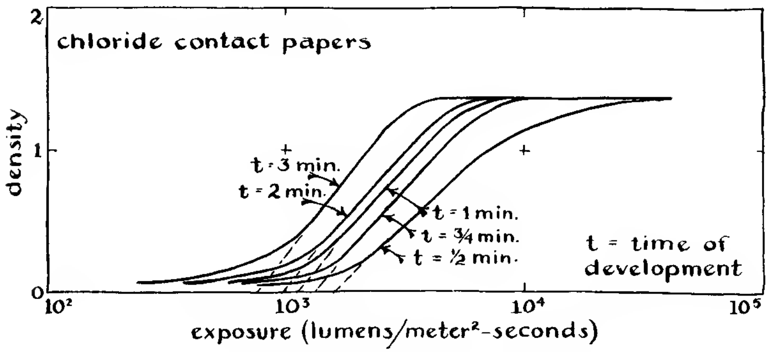

Fig. 16. After Hardy and Perrin. (See footnote 1.)

are illustrated in Figs. 16 and 17. It is to be noted that the contrast of these papers, or slope of the straight segment of the Δ-$\log \Sigma$ curve, does not change much with increasing development time. The contrast is more of an intrinsic property of the emulsion than it is with plates and films. Papers are obtainable commercially in various grades, so that if one paper does not give the desired contrast, another grade is used.

The procedure for exposing and developing papers is different from that recommended for plates and films. Proper contrast is important with plates and films, while density is not so important. On the other hand, correct density is important for papers. The procedure for exposing

bromide paper, for example, is to adjust exposure so that development for 3 minutes yields proper density.

Development for 3 minutes rather than the 2 minutes usually prescribed yields more contrast in the highlights, as a perusal of the curves of Fig. 17 will show. For the exposure range below 10 lumen seconds/m², it will be noted that the inclination of the H and D curve to the abscissa is greater for the 3-minute development than it is for the 2-minute development.

The proper exposure is determined with narrow test strips of paper. When the density is correct, the image shows a

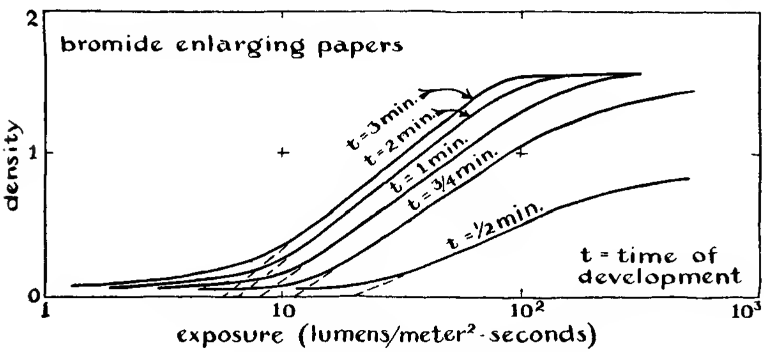

Fig. 17. After Hardy and Perrin. (See footnote 1.)

thin veil of blackening in the highlights, compared with the clear unexposed margins. A common fault in improperly printed negatives arises from overexposure and under-development. *Never develop papers for less than 2 minutes.*

Table XI gives the relative speeds of different papers, so that once the exposure is determined for one grade, that for another may be calculated approximately. These values are not and cannot be precise because of unavoidable variations in manufacture. Nevertheless, the table is of value for practical work.

If, in development, a portion of the print fails to come up at a satisfactory rate, owing to an extra high local density of the negative, development may be accelerated locally by

applying a piece of cotton wet with warm water or simply by warming the film with heat from the fingers, rubbed on the selected spot.

Some of the organic developers, particularly amidol, are poisonous. The toxicity of developers varies for different people, but contact may be avoided if wooden tongs are used for manipulating prints in the developer. (See Fig. 12.) The print is moved around or the solution is stirred as development progresses. Care must be taken not to allow the wooden tongs to come in contact with the acid of the short stop or hypo of the fixing solution, since these chemicals would ruin the developer solution.

Prints are washed conveniently in a cascade of flat pans as illustrated in Fig. 13. As the fixing of each print is completed, it is put in the bottom pan. But before this is done, the print in the top pan is removed, and the print in the second pan is advanced to the top, and so forth, until the bottom pan is emptied to make ready for the one in the hypo bath. The prints, after washing, are laid emulsion side down on a cheesecloth tray to dry.

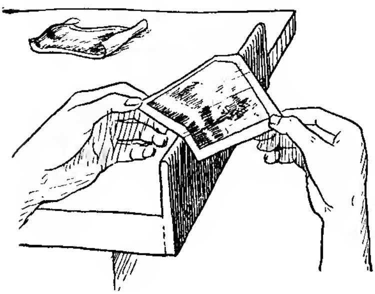

Fig. 18.

As soon as the prints are dry, they are bent along their diagonals in the manner illustrated in Fig. 18 to remove wrinkles. They are then ready for mounting. It may be desirable to flatten them out further by pressing them between the leaves of a book or magazine.

Glossy prints are squeegeed on enameled plates, using a solution of paraffin or Ozokite in benzene to prevent the print from sticking. The solution should be rubbed dry and polished with cheesecloth before the print is squeegeed. Also, for drying glossy prints, chromium-plated brass sheets are now available which do not require paraffin or Ozokite, but only need to be washed and wet with water.

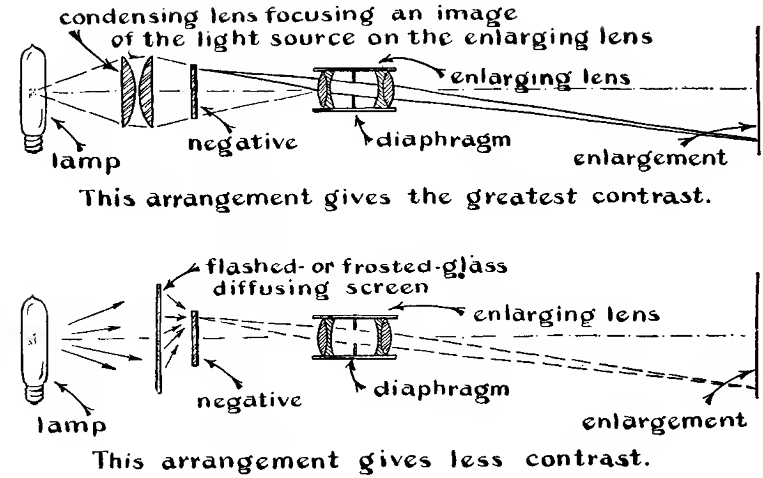

Fig. 19.

Fig. 19 illustrates two arrangements for enlarging. The so-called specular density is involved in the one shown above and the diffuse density in the lower one. The one above is generally used. The lower arrangement is used in portraiture, or whenever contrast is to be avoided.

TABLE XI

RELATIVE EXPOSURES REQUIRED FOR VARIOUS PAPERS

Paper	Soft	Medium	Contrast
Bromide papers	$1\frac{1}{2}$	2	5
Chloride papers	200	300	400

Photographs for publication which require strong contrast should be printed on glossy paper, which exhibits higher contrast than matte paper.

Intensifying and reducing. The function of intensifying is to increase contrast, whereas the function of reducing is primarily to decrease the density. Reducing may, however, increase or decrease contrast or leave it unaltered, depending

on the solutions used. The processes of intensifying and reducing will correct errors in the original development, but they will not satisfactorily correct errors of exposure.

The chromium process of intensification will be treated here. It gives a permanent intensified image, in contrast to the mercury process, which is not permanent. To apply the chromium process, the gelatin should be first bathed in a hardening solution. After this, the emulsion is bleached clear in a mixture of 1 part of the following stock bleaching solution with 10 parts water.

BLEACHING SOLUTION FOR CHROMIUM INTENSIFIER

Potassium bichromate	90 g
Concentrated hydrochloric acid	64 cc
Water to make	1000 cc

The bleached emulsion is then washed for 5 minutes and redeveloped, after which treatment it will exhibit greater contrast. It is then thoroughly fixed and washed. The process may be repeated to obtain even greater contrast. The intensification process does not need to be carried out in the dark.

To obtain extreme contrast the intensified negative is printed on a transparent film, which is then intensified and printed again, and so on, until the desired result is obtained.

Intensification occurs with each photographic process, so that often in the second photographic process (printing) special care is necessary to prevent the development of excessive contrast. It may be necessary to employ a reduction procedure. The various formulas and directions for reducing, with or without change of contrast, are given in *Elementary Photographic Chemistry*.[18]

Some applications of photography. Photographs may be taken in the infrared with a suitably sensitized emulsion, an ordinary lens, and a suitable filter, such as the 88A filter shown in Fig. 7. Heated objects, even a hot electric iron, giving off entirely invisible radiation, can be used for

[18] This book is available from firms dealing in photographic supplies or directly from the Eastman Kodak Company, Rochester, New York.

illumination. Hypersensitizing is particularly effective in infrared photography.

R. W. Wood of Johns Hopkins University and W. H. Wright of Lick Observatory were the first to show some of the striking effects that could be obtained in infrared photography. The penetrating power of infrared photographs, giving clear pictures of objects many miles distant, even through light haze, accounts for the present wide application of infrared photography, especially for aerial mapping.

Photographs taken with ultraviolet light have yielded equally striking results. They may be taken through any of the filters that are opaque for the visible spectrum, such as bromine vapor, nickel sulphate solutions, thin silver films, or alkali-metal films. The image in ultraviolet light may be formed by a thin quartz meniscus lens or a quartz fluorite achromat. Ultraviolet photographs taken out of doors are free of shadows.

From photographs of the moon taken through a silver film, as well as photographs taken with a bromine-vapor filter, R. W. Wood ascertained that a spot close to the crater Aristarchus was apparently covered with a layer of sulphur. Sulphur exhibits a high reflectivity in the visible spectrum and a very low reflectivity in the ultraviolet. The crater appeared black in Wood's ultraviolet pictures, in strong contrast with its surroundings. No other substance on the moon has been identified by means of such convincing evidence.

The camera can be used for making drawings. The object to be copied is photographed, and an enlargement is made of it on matte paper. This is traced as desired with India ink. The paper is then treated with a bleaching solution and the photographic image is removed. India ink is waterproof and unaffected by the bleaching solution.

The following hints may aid in obtaining good results in the photography of apparatus for publication. In general, the object should be photographed against a light background, such as a white wall or sheet. Polished surfaces on

the apparatus will produce halation. The places giving halation (they may be determined by taking a preliminary picture) must be covered with vaseline and whiting. Best results are obtained by side-lighting from an open window or other light source of extended area. A good artificial source is obtained with a battery of photoflood lamps placed in a box covered with either tracing cloth or some other translucent diffusing material. To obtain depth of focus in photographing apparatus, a small aperture and long exposure should be used. The exposure and development should be managed to give contrast and to show detail in the shadows.

Miniature cameras are suited to making quantities of pictures under similar conditions (35 may be taken at each loading). They can be used for copying reference journal articles and even books. The negatives themselves may be used as the record, in which case they may be read with the film turned upside down in an improvised viewing box equipped with a strong reading lens, or they may be projected on a screen. Also, the negative can be printed on motion-picture positive film. This does not require an excessive amount of time, since all the pictures have the same density, and they are processed in lots of 35 at a time. The miniature camera and projector is also useful for lectures. Graphs and illustrations can be printed on a single film in the order required by the lecture.

The photographing of line drawings in pencil is difficult. A process emulsion should be used, and the illumination should strike the paper at oblique incidence to avoid specular reflection from the graphite pencil marks into the camera lens. The exposure and development are managed in such a way as to give maximum contrast.

The details of the application of photography to spectroscopy and astronomy can only be touched upon here. In general, process plates are recommended for photographing spectra. They are best developed with D-28 or D-11 developer until the developed image shows up through the glass on the back of the emulsion.

The region in the Δ-log Σ curve lying well within the latitude range of the emulsion is most suitable for photographing spectrum lines. The most desirable density is about 0.5. The optimum light intensity for observation of the lines on a spectrum plate has a brightness value of about 100 candles/m^2. For much brighter or weaker lights the contrast sensitivity of the eye decreases. "Mixing up the grains" along the length of a weak spectrum line will materially increase its conspicuousness.

Photographic photometry. A spectrogram or stellar photograph usually serves its purpose if the intensity of the light is indicated approximately, provided the angular distribution of the light is recorded with precision. The peculiar suitability of photography for observations of this kind is illustrated by the reference given in a footnote below.[19] Photography may, however, be used to measure the intensity of light quantitatively.

In photographic photometry, the plate is ordinarily used as an indicator to show, by equal densities, when the exposures of two areas are equal, one of the areas being produced by a source of known intensity, and the other by the radiation to be measured. It is important that the two exposures be made under equivalent conditions, that is, equal illumination and time of exposure or equal intervals of illumination if the light is intermittent. Also, it is important to take precautions against errors arising from variations in sensitivity over the surface of the plate.

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[19] This property, which everyone now takes for granted, was explained by Fox Talbot in the early days of photography as follows:

"Groups of figures take no longer to obtain than single figures. . . . the camera depicts them all at once, however numerous they be. . . .

"It is so natural to associate the idea of labour with great complexity and elaborate detail of execution that one is more struck at seeing the thousand florets of an Agrostic depicted with all its capillary branchlets (and so accurately that none of all this multitude shall want its little bivalve calyx, requiring to be examined through a lens) than one is by the picture of the large and simple leaf of an oak or chestnut. But in truth the difficulty is in both cases the same. The one takes no more time to execute than the other for the object which would take the most skillful artist days or weeks to trace or to copy is effected by the boundless powers of natural chemistry in the space of a few seconds."

We will describe two methods of spectral photometry here. There are many possible sources of error in photometric work, and the treatment given here should be supplemented by reference to articles on this subject listed below.[20]

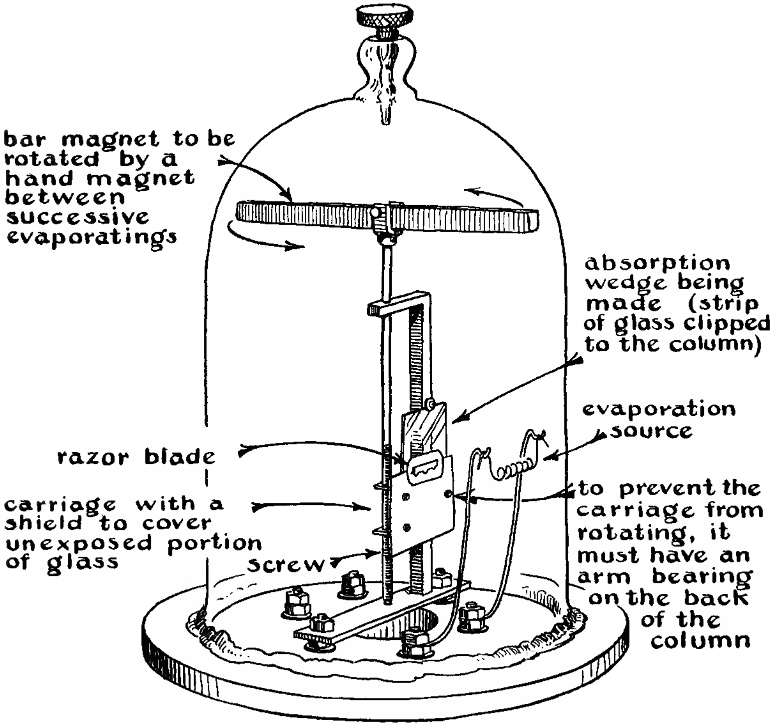


Fig. 20. Making of a step-weakener.

By the first procedure which we will discuss, a so-called step-weakener is mounted directly in front of the entrance slit of the spectrograph. For the first exposure, the slit is

[20] Abney, W. de W., "On the Variation in Gradation of a Developed Photographic Image When Impressed by Monochromatic Light of Different Wave-lengths," *Roy. Soc., Proc.*, *68*, 300 (1901).

Harrison, G. R., "Instruments and Methods Used for Measuring Spectral Light Intensities by Photography," *J. O. S. A.*, *19*, 267 (1929).

Jones, L. A., "Photographic Spectrophotometry in the Ultraviolet Region," *National Research Council, Bull.*, No. 61, 109 (1927).

Jones, L. A., and Sandvik, O., "Spectral Distribution of Sensitivity of Photographic Materials," *J. O. S. A.*, *12*, 401 (1926).

illuminated through the step-weakener with the light to be measured. For the comparison exposure the slit is then illuminated an equal time by the light of known intensity and known spectral distribution, this exposure being made adjacent to the first exposure.

The step-weakener may be a glass or quartz plate coated with strips of platinum (or some other metal) of increasing opacity, or it may be a series of neutral filters of gelatin. The illumination along the slit, which would otherwise be uniform, is attenuated by the step-weakener in varying amounts, usually in geometrical proportion.

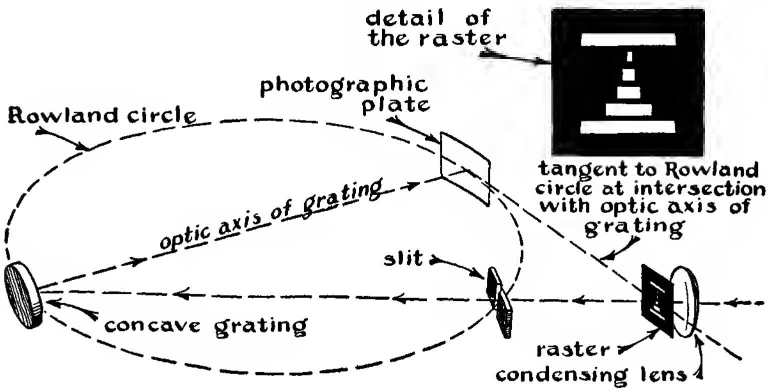


Fig. 21.

The step-weakener is difficult to make and calibrate. Fig. 20 illustrates a procedure for making one by evaporation.

From the calibration of the step-weakener at the wave length in question one can determine the relative light intensities of the different steps. To obtain the calibration, the densities of the various strips of the step-weakener are measured on a microphotometer.

A photograph of the raster shown in Fig. 21 or a raster cut out of thin sheet metal can be used instead of a step-weakener. The use of a raster avoids the necessity for calibration. In a uniform beam of parallel light the quantity of light transmitted by each element of the raster is deter-

mined by its area. The use of a raster requires an astigmatic optical system. The raster is ordinarily mounted so that, in a vertical azimuth its image is focused on the slit, whereas in a horizontal azimuth the parallel light transmitted by it is focused on the slit.

Fig. 21 shows the ingenious way in which Frerichs has used a raster, taking advantage of the natural astigmatism of a Rowland grating setup.[21] In this setup, adjacent areas of the spectral image vary in intensity in the ratio 16:1:2:4:8:16. Fig. 22 illustrates the method of determining the relative intensities of two or more lines. The lines must be near each other in the spectrum, so that the differences in

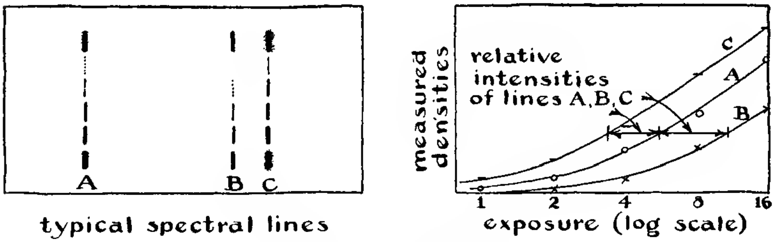


Fig. 22. After Frerichs.[21]

sensitivity of the plate for the wave lengths involved are negligible and so that the H and D curves for each wave length are the same. Three lines photographed through the raster by this setup are illustrated. The densities of the segments of the photographed lines are measured with a microphotometer, and plotted as shown. It is to be noted that the scale of abscissa is logarithmic, the interval in abscissa being equal for each step of the raster. Each spectral line determines an H and D curve, and the lateral displacements necessary to bring the three H and D curves into coincidence determine the relative intensities of the lines. By this procedure an accuracy of about 3 per cent can be expected.

[21] Frerichs, R., "Photographische Spektralphotometrie," *Handbuch der Physik*, Vol. 19, Chapter 23. Berlin: Julius Springer, 1928.

CHAPTER XII

Heat and High Temperature

IN this chapter we will first consider some of the elementary aspects of the theory of heat transfer. Following this we will deal with various techniques of obtaining high temperatures, of temperature control, and of temperature measurement.

Heat conduction. The steady state. The rate Φ (expressed in calories per second) at which heat flows across an isothermal surface element of area A, in a homogeneous medium, is proportional to A, to the conductivity of the material, K, and to the temperature gradient dT/dx perpendicular to the surface, thus:

$$\Phi = -KA\frac{dT}{dx} \text{ calories/sec.} \tag{1}$$

In the case of a rectangular parallelopiped with opposite ends maintained at the temperatures T_1 and T_2, Eq. 1, when integrated, becomes

$$\Phi = -\frac{KA}{x}(T_2 - T_1) \text{ calories/sec.,} \tag{2}$$

in which A is the cross-section area of the parallelopiped perpendicular to the temperature gradient and x is the separation between the isothermal surfaces T_1 and T_2. Here K is assumed to be constant in the temperature range between T_1 and T_2. Values of the heat conductivity for various materials are given in Table I.

TABLE I

THERMAL CONDUCTIVITY, K, DIFFUSIVITY, h, AND RELAXATION TIME, τ, FOR AN INFINITE SLAB OF 2 CM THICKNESS ($x_0 = 1$ CM)

Material (at room temperature, unless otherwise specified)	K (cal./cm/sec./°C.)	h^2 (cm²/sec.)	τ (sec.)
Aluminum[a]	0.480	0.826	0.49
Bismuth[a]	0.0194	0.0678	6.0
Brass (yellow)[a]	0.204	0.339	1.19
Constantan (60 Cu 40 Ni)[b]	0.054	0.062	6.5
Copper[a]	0.918	1.133	.357
Gold[a]	0.700	1.182	.34
Invar[c]	0.026	0.02	20
Wrought iron and mild steel[a]	0.144	0.173	2.3
Cast iron and carbon steel[a]	0.11	0.12	3.3
Lead[b]	0.083	0.209	1.9
Mercury[a]	0.148	0.0327	12.4
Monel metal[d]	0.06	0.056	7.2
Nichrome or Chromel[d]	0.032	0.034	11.9
Nickel[d]	0.215	0.23	1.8
Platinum[d]	0.167	0.239	1.69
Silver[a]	1.006	1.737	0.233
Tungsten: Room temperature[d]	0.38	0.59	0.69
1400°C.[d]	0.258	0.315	1.28
2100°C.[d]	0.296	0.325	1.24
Bonded silicon carbide, 25° to 1000°C.[e]	0.024	0.055	7.3
Graphite, 0° to 100° C.[d]	0.315	1.2	0.34
Quartz glass: 0°C.[d]	0.0033	0.0083	49
1000°C.[d]	0.0064	0.0105	38
Hard porcelain, 20° to 1000°C.[d]	0.003 to 0.004	0.0028 to 0.0056	144 to 72
Fired natural soapstone[d]	0.003 to 0.0067	—	—
MgO[d]	0.0015 to 0.0036	0.00167 to 0.00333	240 to 120
Al_2O_3[d]	0.0016 to 0.0084	0.0023 to 0.0116	176 to 35
Sintered Al_2O_3, 900°C.[d]	0.013	0.0119	34
Mica[d]	0.0008 to 0.0014	0.00132 to 0.00232	306 to 174
Glass[a]	0.0024	0.0057	71
Air, 0°C.[a]	0.000055	0.179	2.3
Asbestos (loose)[a]	0.0004	0.0035	116
Average firebrick, 0° to 800°C.[a]	0.004	0.0074	55
Concrete (stone), 20° to 1000°C.[a]	0.0027	0.0056	72
Cork (ground)[a]	0.00012	0.0017	238
Paraffin[a]	0.00061	0.001	404
Water[a]	0.00143	0.00143	283
Pine wood: Across grain	0.0002	0.0012	340
With grain	0.0006	0.0036	122

[a] Ingersoll, L. R., and Zobel, O. J., *An Introduction to the Mathematical Theory of Heat Conduction*. Boston: Ginn and Company, 1913.

[b] Fowle, F. E., *Smithsonian Physical Tables*. Washington: The Smithsonian Institution, 1934.

[c] King, W. J., *Mechanical Engineering*, *54*, 275 (1932).

[d] Espe, W., and Knoll, M., *Werkstoffkunde der Hochvakuumtechnik*. Julius Springer, 1932.

[e] Hering, C., *Am. I. E. E., J.*, *29*, 485 (1910).

Shape factors. For many of the actual cases encountered, the geometry is not so simple as it is with the parallelopiped, and the integration of Eq. 1 may be quite difficult. Generally, however, the integral may be expressed by an equation of the form

$$\Phi = -KS(T_2 - T_1) \text{ calories/sec.,} \tag{3}$$

in which S, the so-called shape factor, depends upon the size and shape of the space between two isothermal surfaces maintained at temperatures T_1 and T_2.

For a rectangular parallelopiped the shape factor, from Eq. 2, is

$$S = \frac{A}{x}. \tag{4}$$

For two concentric cylindrical isothermal surfaces (long in comparison with their radii) of length l, maintained at temperatures T_1 and T_2, respectively, the value of S in terms of l and their radii r_1 and r_2 is

$$S = \frac{2.73l}{\log_{10} r_2/r_1}. \tag{5}$$

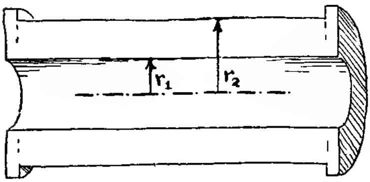
For two concentric spherical isothermal surfaces, one of radius r_1 at temperature T_1 and the other of radius r_2 at temperature T_2, the shape factor is

$$S = \frac{4\pi}{\left(\frac{1}{r_1} - \frac{1}{r_2}\right)}. \tag{6}$$

A heat problem which often arises in the laboratory requires the estimation of the heat loss of an electric furnace. The inner furnace wall, which is approximately at uniform temperature, is taken as one isothermal surface, and the outer surface of the furnace, at somewhat above room temperature, is taken as the other isothermal surface. Langmuir, Adams, and Meikle have given shape factors for several special cases which may be applied to problems of this type.[1] However, to make an estimate of heat loss of a

[1] Langmuir, I., Adams, E. Q., and Meikle, G. S., *Amer. Electrochem. Soc., Trans.*, *24*, 53 (1913).

cylindrical furnace, if the inner furnace tube is long and surrounded by a layer of insulating material as shown in Fig. 1, we may apply Eq. 5. Or, for the case shown in Fig. 2, we may apply Eq. 6, taking r_1 and r_2 as the dimensions of the approximating spherical surfaces, indicated in the figure by dotted lines. These estimates are not expected to be precise, but they are usually accurate enough to settle the questions which arise when one designs a furnace.



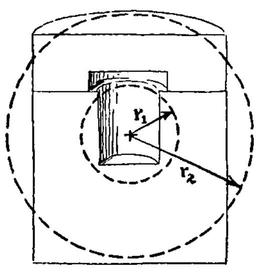
see Fig. 17

Fig. 1.

The shape factor can also be determined experimentally, using the similarity between the law for the flow of heat, Eq. 1, and Ohm's law. The experimental determination of S is accomplished by measuring the electrical shape factor, S', for wooden models that simulate the inner and outer isothermal temperature surfaces of the heat problem in question. These model surfaces are coated with copper foil and serve as electrodes. The region between these surfaces is filled with a saturated solution of copper sulphate with $\frac{1}{2}$ per cent (by volume) sulphuric acid added. The conductance of this solution is determined by applying alternating voltage to the copper electrodes. Alternating current is used to prevent polarization at the electrodes. The equation giving the electrical shape factor is

$$i = -K'S'V, \tag{7}$$

V and i being the measured voltage drop and current. K', the electrical conductivity of the solution, may be determined by a separate experiment, using a box of cross section A' and length x' with copper end plates. For this box the shape factor is A'/x' (as in Eq. 4). To transform



see Fig. 19

Fig. 2.

S' to S, divide S' by the scale factor to which the model was constructed. For example, if the model was made to half scale, $S = 2S'$.

Heat conduction. The nonsteady state. The thermal behavior of a homogeneous body is described in a Cartesian system of coördinates by the following fundamental differential equation:

$$\frac{dT}{dt} = \frac{K}{\rho c}\left(\frac{d^2T}{dx^2} + \frac{d^2T}{dy^2} + \frac{d^2T}{dz^2}\right). \tag{8}$$

Here t is the time, T is the temperature of a point in the body represented by the coördinates x, y, and z, dT/dt is the rate at which this temperature changes, and K, ρ, and c represent physical quantities for the material of which the body is composed, namely, the heat conductivity, density, and specific heat. The combination of these constants in the form $h^2 = K/\rho c$ is convenient. h is called the thermal diffusivity of the material.

In one dimension, Eq. 8 takes the form

$$\frac{dT}{dt} = \frac{K}{\rho c}\frac{d^2T}{dx^2}. \tag{9}$$

If dT/dt equals zero, and if we integrate d^2T/dx^2 once, we get the equation which represents the steady-state problem:

$$\frac{dT}{dx} = M. \tag{10}$$

From physical considerations, the integration constant M is seen to have the meaning

$$M = -\frac{\Phi}{KA}, \quad \text{and} \quad \Phi = -KA\frac{dT}{dx}, \tag{11}$$

which is the same as Eq. 1.

A more general form of Eq. 8 includes an added term to take account of energy transformations associated with a change of state, and so forth, which will not be considered here.

There are infinitely many solutions to the fundamental differential equation, Eq. 8. Those which are appropriate

for a given problem usually comprise an infinite series, the sum of which conforms to the requirements of the geometry of the body, and to the so-called boundary conditions set forth in the problem. The mathematical procedures involved in getting the series required for a particular problem were originally developed by Fourier over a hundred years ago; and these procedures have been extended by other mathematicians to include a great variety of more or less complicated cases.[2] Here, without taking up the mathematical procedures involved, we will discuss the results of their application to some typical heat problems.[3]

The infinite slab. First, let us determine the temperature at various points in a plane-parallel slab which, to start with, is at a uniform temperature T_0. We will find the temperature at various places in the slab as a function of the time which elapses after the slab has been immersed into an environment maintained at a fixed temperature T_1. We will assume that T_1 is lower than T_0. (The changes required to apply the results so obtained for the opposite case, in which T_1 is higher than T_0, are obvious.) Practically, if the extension of the slab is great compared to its thickness, this becomes a one-dimensional problem, and to describe it we will take a Cartesian coördinate system which is oriented so that the faces of the slab coincide with the planes $x = +x_0$ and $-x_0$.

The solution of Eq. 8, which we want, is a series, the terms of which depend on both x and t. The sum of the series yields a uniform temperature throughout the slab at $t = 0$; and also at all times it gives a temperature gradient at the surfaces which conforms to the requirements of Newton's law of cooling.

Newton's law of cooling states that the heat lost per unit

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[2] Carslaw, H. S., *Introduction to the Mathematical Theory of the Conduction of Heat in Solids*, Second Edition. London: The Macmillan Company, 1921.

Ingersoll, L. R., and Zobel, O. J., *The Mathematical Theory of Heat Conduction, With Engineering and Geological Applications.* Boston: Ginn and Company, 1913.

[3] I am indebted to Dr. R. M. Langer for the treatment of nonsteady heat flow presented in this chapter.

area of surface, W, by the slab to its environment, is proportional to the difference between the surface temperature T_{x_0} and the temperature of the bulk of the medium in which it is immersed, T_1:

$$W = N(T_{x_0} - T_1) \text{ calories/sec./cm}^2. \tag{12}$$

W may be resolved into heat lost by radiation, $W_{\text{rad.}}$, and heat lost by convection, W_{conv}. The temperature gradient at the surface is determined by the value of W and the thermal conductivity of the material of which the slab is composed.

Stated algebraically, the boundary conditions which our solution of Eq. 8 must satisfy are

$$\text{at } t = 0;\ T = T_0 \text{ throughout the slab} \tag{13}$$

and, for all values of t;

$$\text{at } x = x_0 \qquad \frac{dT}{dx} = -\frac{N}{K}(T_{x_0} - T_1) \tag{14a}$$

and also at

$$x = -x_0 \qquad \frac{dT}{dx} = \frac{N}{K}(T_{x_0} - T_1). \tag{14b}$$

The solution of Eq. 8 which satisfies these conditions is

$$T = T_1 + \frac{4}{\pi}(T_0 - T_1)\sum_0^\infty \frac{\sin\dfrac{a_n\pi}{2}}{a_n\left(1 + \dfrac{\sin a_n\pi}{a_n\pi}\right)} e^{-\frac{a_n^2\pi^2h^2t}{4x_0^2}} \cos\frac{a_n\pi}{2}\frac{x}{x_0}, \tag{15}$$

where the a_n's are roots of the transcendental equation

$$\frac{2x_0N}{\pi a_nK} = \tan\frac{a_n\pi}{2}. \tag{16}$$

The values of a_n may be determined graphically from the intersection points of the two functions of a_n,

$$y = \frac{\pi a_nK}{2x_0N}, \text{ and } y = \cot\frac{a_n\pi}{2}. \tag{17}$$

Before discussing various aspects of this solution, let us make the substitution,

$$\tau = \frac{4x_0^2}{\pi^2h^2}, \tag{18}$$

in the exponential terms. τ is called the relaxation time. The reason for this will appear presently.

At the beginning, that is, when t has small values compared with τ, the accurate expression for T requires several terms of the series given by Eq. 15, in spite of the fact that the series is a rapidly converging one. However, soon after $t = \tau$, all the exponential terms become insignificant except the first one ($n = 1$). This is because a_1 is smaller than the other values of a_n. Soon after $t = \tau$, Eq. 15 reduces to

$$T = T_1 + \frac{4}{\pi}(T_0 - T_1)\left[\frac{\sin\dfrac{a_1\pi}{2}}{a_1\left(1 + \dfrac{\sin a_1\pi}{a_1\pi}\right)} e^{-a_1^2\frac{t}{\tau}} \cos a_1\frac{\pi}{2}\frac{x}{x_0}\right]. \tag{19}$$

The first factor in the brackets is a constant, the second determines the decay of the temperature difference $(T - T_1)$, and the third factor is the space distribution function for the temperature. The relaxation time is evidently the interval required for the temperature, initially uniform, to assume approximately the distribution given by the last factor in Eq. 19.

The value of a_1 for a body (with vertical sides) in air at room temperature is obtained from Eqs. 35, 48, 12, and 16:

$$W_{\text{conv.}} = 1.3 \times 10^{-4}(T_0 - T_{x_0}) \text{ calorie/sec./cm}^2. \tag{35a}$$

$$W_{\text{rad.}} = 1.5 \times 10^{-4}(T_0 - T_{x_0}) \text{ calorie/sec./cm}^2. \tag{48a}$$

Thus

$$N = 2.8 \times 10^{-4} \text{ calorie/sec./cm}^2/^\circ\text{C}.$$

To illustrate how Eq. 19 may be applied, let us consider the case of a telescope mirror of 2 cm thickness which is to be tested by the Foucault knife-edge test. For a reliable test, if this mirror is brought from a room in which it is either warmer or cooler than the air of the testing room, it will be necessary to wait until the mirror has adjusted itself to the new temperature. If the glass is 15 cm or more in diameter and is exposed to the room air on both sides, we may regard it as an infinite slab and apply Eq. 19 to determine its thermal

behavior. For the glass we may take $K = .0024$ and $h^2 = .0057$. This gives $\tau = 71$ seconds, and by means of Eq. 16, we get $a_1 = 0.219$.

Substituting this value of a_1, Eq. 19 can be written in the form

$$\log_{10}\left(\frac{T_1 - T_x}{T_1 - T_0}\right) = -3 \times 10^{-4}t + 0.15 + \log_{10}(\cos 0.34x). \quad (20)$$

This solution is valid after more than 71 seconds have elapsed. To get the thermal behavior at the start, the logarithm of $(T_1 - T_x)/(T_1 - T_0)$ can be plotted as ordinate against t as abscissa. The series of parallel straight lines obtained for $t > 71$ seconds are then extrapolated to the common point where the abscissa and the ordinate are equal to zero, bearing in mind that $T_{x=\pm x_0}$ changes rapidly with time when $t=0$ and $T_{x=0}$ changes very slowly. This method is not very precise, and a more exact solution is to be obtained from Eq. 15. This formula is rather difficult to manage, except in special cases. Two of these are treated below.

Eq. 15 can be simplified for the extreme cases of relatively fast cooling, where $Nx_0/K >> 1$, and relatively slow cooling, where $Nx_0/K << 1$. In the first case a_n is approximately $(2n + 1)$, $\sin(a_n\pi/2)$ is $(-1)^n$, and the expression for temperature simplifies to

$$T = T_1 + \frac{4}{\pi}(T_0 - T_1)\sum_0^\infty \frac{(-1)^n}{2n+1} e^{-\frac{(2n+1)^2t}{\tau}} \cos (2n + 1)\frac{\pi x}{2x_0}. \quad (21)$$

For slow cooling, where $Nx_0/K << 1$, the slab is practically isothermal, and the temperature is given by

$$T = T_1 + (T_0 - T_1)e^{\frac{Nh^2}{Kx_0}t}. \quad (22)$$

The solution of problems of this character will be useful to the experimenter when he encounters questions of design involving the accommodation of objects to changes of temperature.

The application to optical testing has already been discussed. In optical testing with the Foucault knife-edge test, lack of thermal equilibrium distorts the figure of an optical surface and gives rise to troublesome convection currents.

The relaxation time. The relaxation time for a cylinder is approximately half that for a slab, when $2x_0$, the thickness of the slab, and $2r_0$, the diameter of the cylinder, are equal. The relaxation time for a sphere or cube is approximately one quarter of that for a corresponding slab. In most of the nonsteady-state problems encountered, it is sufficient to know the relaxation time. The relaxation time can be interpreted as the time for a heat pulse to travel into the center of the slab, a distance x_0. The relaxation times are given in Table I for a slab thickness of 2 cm ($x_0 = 1$ cm) for different materials. It must be remembered that for different values of x_0 the time required for the heat to penetrate to the center of the slab is proportional to x_0^2.

The relaxation time for graphite, which is approximately the same as that for copper, is especially noteworthy. The extreme values for τ given in Table I are about $\frac{1}{4}$ second and 404 seconds for silver and paraffin respectively.

Periodic temperatures. Let us consider a slab of thickness x_0 having a harmonic surface temperature $T_1 = A \cos \omega t$. If τ is the relaxation time for the slab, the interior temperature is given by the expression

$$T = A \cos \omega t - \frac{4A\omega^2\tau^2}{\pi} \sum_0^\infty \frac{\dfrac{(-1)^n}{(2n+1)^5}}{1 + \dfrac{\omega^2\tau^2}{(2n+1)^4}} \left\{ \frac{(2n+1)^4}{\omega^2\tau^2} e^{-(2n+1)^2 \frac{t}{\tau}} - \cos \omega t + \frac{(2n+1)^2}{\omega\tau} \sin \omega t \right\} \cos (2n+1)\frac{\pi x}{2x_0}. \tag{23}$$

The exponential term can be neglected after the relaxation time, and the temperature is then given by the summation. Unless $\omega\tau >> 1$, the convergence of the series is rapid

enough to make the first term a good approximation for it:

$$T = A\left\{\left(1 - \frac{4}{\pi}\frac{\omega^2\tau^2}{1+\omega^2\tau^2}\cos\frac{\pi x}{2x_0}\right)\cos\omega t + \left(\frac{4\omega\tau}{\pi(1+\omega^2\tau^2)}\right)\sin\omega t\cos\frac{\pi x}{2x_0}\right\}. \tag{24}$$

The product $\omega\tau$ is the ratio of the relaxation time to the period of the impressed harmonic temperature multiplied by 2π. If $\omega\tau$ is small, the plate follows the impressed temperature closely with an out-of-phase component, $\sin\omega t$, proportional to $\omega\tau$, and the amplitude of the temperature fluctuation is proportional to $\cos(\pi x/2x_0)$.

When $\omega\tau >> 1$, the temperature near the surface is approximately the same as if the slab were infinitely thick, while the temperature in the center is practically constant.

The temperature at a distance x from the surface of an infinitely thick slab is given, after a long time, by the expression

$$T = Ae^{-\sqrt{\frac{\omega}{2}}\frac{x}{h}}\cos\left(\omega t - \sqrt{\frac{\omega}{2}}\frac{x}{h}\right), \tag{25}$$

where $A\cos\omega t$ represents the surface temperature. Thus, the amplitude decreases exponentially with depth according to the law $e^{-\sqrt{\frac{\omega}{2}}\frac{x}{h}}$. There is a time lag of $\sqrt{x^2/2\omega h^2}$ in its harmonic variation, relative to the phase of the surface temperature.

The sphere. When a sphere or cylinder that is initially at a uniform temperature T_0 is introduced into a medium at a lower temperature T_1, the equations similar to those for the slab are:

For a sphere of radius r_0,

$$T = T_1 + \frac{4Nr_0^2}{\pi K}(T_0 - T_1)\sum_1^\infty \frac{\sin\frac{\alpha_n\pi}{2}}{\alpha_n\left(\frac{\alpha_n\pi}{2} - \sin\alpha_n\pi\right)} e^{-\frac{\alpha_n^2\pi^2h^2t}{4r_0^2}}\frac{\sin\frac{\alpha_n\pi r}{2r_0}}{r}, \tag{26}$$

where α_n are the roots of

$$\tan\frac{\alpha_n\pi}{2} = \frac{\frac{\alpha_n\pi}{2}}{1 - \frac{Nr_0}{K}}, \tag{27}$$

and after the relaxation time the term representing the temperature distribution (corresponding to cos $(a_1\pi x/2x_0)$ in Eq. 15) is

$$\left\{\frac{\sin\dfrac{\alpha_n\pi r}{2r_0}}{r}\right\}.$$

When $Nr_0/K \approx 1$, the temperature is given approximately by the expression

$$T = T_1 + \frac{8}{\pi^2}(T_0 - T_1)\frac{Nr_0^2}{K}\sum_0^\infty \frac{(-1)^n}{(2n+1)^2} e^{-\frac{(2n+1)^2\pi^2h^2t}{4r_0^2}} \frac{\sin\dfrac{(2n+1)\pi r}{2r_0}}{r}. \quad (28)$$

When $Nr_0/K >> 1$, that is, for relatively fast cooling, the temperature is given approximately by

$$T = T_1 + \frac{2r_0}{\pi}(T_0 - T_1)\sum_1^\infty \frac{(-1)^{n-1}}{n\left(1-\dfrac{K}{Nr_0}\right)^2} e^{-\frac{n^2\pi^2h^2t}{r_0^2}\left(1-\frac{K}{Nr_0}\right)^2} \times \frac{\sin\left(1-\dfrac{K}{Nr_0}\right)\dfrac{n\pi r}{r_0}}{r}. \quad (29)$$

In the case of slow cooling, in which $Nr_0/K << 1$, the temperature is sensibly the same throughout the sphere, and its change with time is given by the expression

$$T = T_1 + (T_0 - T_1)e^{-\frac{3Nh^2t}{Kr_0}}. \quad (30)$$

The cylinder. For a cylinder of radius r_0, the temperature in terms of the well-tabulated Bessel functions J_0 and J_1 is

$$T = T_1 + 2(T_0 - T_1)\sum_1^\infty \frac{1}{\mu_n\left(1+\dfrac{K^2\mu_n^2}{N^2r_0^2}\right)J_1(\mu_n)} e^{\frac{-\mu_n^2h^2t}{r_0^2}} J_0\left(\mu_n\frac{r}{r_0}\right), \quad (31)$$

where the μ_n's are roots of the equation

$$\frac{\mu_n}{r_0}J_1(\mu_n) = \frac{N}{K}J_0(\mu_n).$$

In limiting cases the μ_n disappear. For example, when $Nr_0/K >> 1$, that is, when we have fast cooling, the μ_n's

are close to the roots of $J_0(\mu_n) = 0$, and the temperature is given approximately by the equation

$$T = T_1 + 2\,(T_0 - T_1)\left\{\frac{1}{1.25}\,e^{-\left[2.4\frac{h}{r_0}\left(1+\frac{K}{Nr_0}\right)\right]^2 t} J_0\left(2.4\left[1+\frac{K}{Nr_0}\right]\frac{r}{r_0}\right) - \frac{1}{1.87}\,e^{-\left[5.52\frac{h}{r_0}\left(1+\frac{K}{Nr_0}\right)\right]^2 t} J_0\left(5.5\left[1+\frac{K}{Nr_0}\right]\frac{r}{r_0}\right) + \text{etc.}\right\}. \tag{32}$$

Temperatures at the center are obtained without the help of tables of Bessel functions because $J(0) = 1$.

When $Nr_0/K << 1$, with practically uniform temperature throughout the cylinder,

$$T = T_1 + (T_0 - T_1)\,e^{-\frac{2Nh^2t}{Kr_0}}. \tag{33}$$

If $Nr_0/K \approx 1$, the first term of Eq. 31 dominates after the relaxation time. The Bessel function can be expanded, and then the temperature is given by

$$T = T_1 + (T_0 - T_1)\left(1+\frac{2K}{Nr_0}\right)\left\{\frac{\left(1+\frac{2K}{Nr_0}\right) - \left(\frac{r}{r_0}\right)^2}{1+\frac{2K}{Nr_0}+\frac{4K^2}{N^2r_0^2}}\,e^{\frac{-4h^2t}{r_0^2\left(1+\frac{2K}{Nr_0}\right)}}\right\}. \tag{34}$$

Heat transfer by free convection. Except for a few special cases, the estimation of heat loss by free convection is quite complicated or even impossible. The special cases which have been solved include plane surfaces and wires cooled by convection. The work on this subject up to 1933 has been summarized by W. J. King.[4] Among the various methods for calculating convection losses, that of Langmuir is the simplest.[5] His method applies when the surfaces are small, such as those encountered in the laboratory. As it

[4] King, W. J., *Mechanical Engineering*, *54*, 190, 275, 347, 410, 492, 560 (1932).

[5] Langmuir, I., *Amer. Electrochem. Soc., Trans.*, *23*, 299 (1913); *Phys. Rev.*, *34*, 401 (1912).

Rice, C. W., *International Critical Tables*, *5*, 234. New York: McGraw-Hill Book Company, 1929.

applies to a vertical surface, his method consists of calculating the heat conduction through a postulated stagnant air film of 0.45 cm thickness, thus:

$$W = \frac{-K}{0.45}(T_2 - T_1) \text{ calories/sec./cm}^2. \tag{35}$$

Here K is the thermal conductivity for air, T_1 is the absolute temperature of the vertical surface, and T_2 is the ambient temperature. A more complete theory shows that W is proportional to $(T_2 - T_1)^{5/4}$ and to the fourth root of the height of the vertical surface. K, in Eq. 35, is not independent of temperature, and, except for small temperature drops, the heat transfer is given by the expression

$$W = \frac{-1}{0.45}\int_{T_2}^{T_1} KdT = -\frac{(\phi_2 - \phi_1)}{0.45} \text{ calories/sec./cm}^2. \tag{36}$$

Values of ϕ for air are given in Table II to facilitate calculation. These values are defined by the expression

$$\phi = \int_0^T KdT. \tag{37}$$

TABLE II

VALUES OF ϕ FOR AIR

Temperature (°A.)	Calories/sec./cm
0	0
100	0.00098
200	0.00401
300	0.00924
400	0.0160
500	0.0243
700	0.0451
900	0.0709
1100	0.1017
1300	0.1376
1500	0.1776
1700	0.222
1900	0.271
2100	0.325
2300	0.384
2500	0.447

Langmuir found that heat losses by free convection from a horizontal surface facing upward are 10 per cent greater than they are from a vertical surface, and they are 50 per cent less from a surface facing downward than they are from a vertical surface.

The procedure for calculating the convection losses from wires is also treated by Langmuir.

Heat transfer by radiation. The energy emitted by a surface of area A radiating the heat spectrum between the wave lengths λ and $\lambda + d\lambda$ is

$$\Phi_{d\lambda} = \pi\epsilon_\lambda J_\lambda d\lambda \text{ calories/sec.} \tag{38}$$

This represents the summation of energy in respect to the solid angle over the hemisphere (angle 2π steradians). Here ϵ_λ is the emissivity of the surface. This is the ratio of the emission of the surface to that which would obtain for a "black body" at the same temperature. J_λ is the energy radiated per unit solid angle by a black body of the same area at wave length λ for a unit wave-length range, $d\lambda = 1$ cm.

So-called black-body radiation is defined as the thermal radiation coming from the surface of a body which is in temperature equilibrium with all of its surroundings. For example, the inner surface of a cavity in an opaque material at a uniform temperature emits black-body radiation. In fact, black-body radiation is obtained experimentally from just such a cavity. The wall of the cavity is pierced to form a small aperture to serve as an outlet for the radiation, the hole being small enough not to disturb the equilibrium perceptibly. The name *black-body radiation* comes indirectly from Kirchoff's law, which states that the emission and absorption coefficients of any body are equal. A black body with an absorption coefficient of unity, $\alpha_\lambda = 1$, therefore, by Kirchoff's law, has an emission coefficient of unity, $\epsilon_\lambda = 1$.

The Planck expression for J_λ is a function of the wave length, λ, and the absolute temperature, T.

$$J_\lambda = \frac{Ac_1}{\lambda^5}\left(\frac{1}{e^{\frac{c_2}{\lambda T}} - 1}\right) \text{calories/sec./cm/steradian.} \tag{39}$$

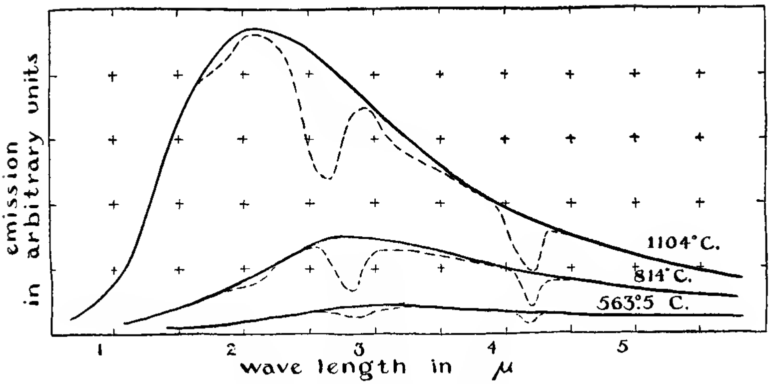

Fig. 3. After Jean Lecomte.

This formula describes the distribution of energy in the heat spectrum, and its plot against λ at different temperatures is illustrated in Fig. 3.

For $\lambda T = 0.3$ this expression is approximated to within 1 per cent by the so-called Wiens formula,

$$J'_\lambda = \frac{Ac_1}{\lambda^5} e^{-\frac{c_2}{\lambda T}} \text{ calories/sec./cm/steradian.} \tag{40}$$

As λT becomes $<< 0.3$, J'_λ becomes asymptotic to J_λ.

For $\lambda T = 80$ the expression is approximated to within 1 per cent by the so-called Rayleigh-Jeans formula,

$$J''_\lambda = \frac{Ac_1}{c_2\lambda^4} T \text{ calories/sec./cm/steradian.} \tag{41}$$

As λT becomes $>> 80$, J''_λ becomes asymptotic to J_λ. The values of the constants c_1 and c_2, where λ is expressed in centimeters, are $c_1 = 2.81 \times 10^{-13}$ calorie/sec./cm^2/unit solid angle; and $c_2 = 1.432 \times 10^8$ cm degrees.

The total heat lost by a unit area of the surface of a "black body" is the quantity expressed by Eq. 38 integrated over all wave lengths. This gives Stefan's formula:

$$\Phi = \pi \int J_\lambda d\lambda = A\sigma T^4 \text{ calories/sec.} \tag{42}$$

Most surfaces have a total emission which may be expressed as

$$\Phi = A\epsilon_T \sigma T^4 \text{ calories/sec.} \tag{43}$$

Here σ has the value of 1.37×10^{-12} calorie/sec./cm²/degree⁴.

The heat emitted by a flat surface of area A into a cone which is defined by a solid angle $d\Omega$ is

$$d\Phi = A \cos \theta \frac{d\Omega}{\pi} \epsilon_T \sigma T^4 \text{ calories/sec.} \tag{44}$$

Here $A \cos \theta$ is the projected area of the source and $d\Omega/\pi$ is the fraction of the total heat emitted in the direction θ defined by the element $d\Omega$.

ϵ_T is an emissivity averaged over all wave lengths, and it is ordinarily "constant" only for a small temperature range. For porous nonmetallic substances it is very nearly unity, regardless of the color of the material. Naturally, the visible color of a body does not determine its infrared "color." Some bodies, such as white lead, are almost completely black throughout the heat spectrum, while the reverse is true for other substances, notably soot and black paper, both of which are transparent for the long wave-length end of the heat spectrum. ϵ_T for aluminum paints, around room temperature, varies between 0.3 and 0.5. For nonmetallic pigment paints $\epsilon_T = 1$.

For clean metals, ϵ_T varies with the temperature in such a way that the total emissivity is conveniently represented by an expression of the form

$$\Phi = AMT^m \text{ calories/sec.} \tag{45}$$

Here M and m are constants. Values of M and m for some common metals are given in Table III.

TABLE III

RADIATION CONSTANTS OF METALS

Metal	Temperature Range (°K.)	M	m
Silver	610 to 980	7.16×10^{-14}	4.1
Platinum	640 to 1150	5.50×10^{-16}	5.0
Nickel	463 to 1280	2.39×10^{-15}	4.65
Iron	700 to 1300	7.65×10^{-18}	5.55
Nichrome	325 to 1310	4.30×10^{-13}	4.1

Smithsonian Tables, 1934, page 324.

The heat transfer by radiation between two parallel black isothermal surfaces of area A at absolute temperatures T_1 and T_2, which are separated by a small distance, is

$$W = \sigma(T_2^4 - T_1^4) \text{ calories/sec./cm}^2 \tag{46}$$

$$W = 1.37\left\{\left(\frac{T_2}{1000}\right)^4 - \left(\frac{T_1}{1000}\right)^4\right\} \text{ calories/sec./cm}^2. \tag{47}$$

If the temperature difference, $(T_2 - T_1)$, is small, this heat transfer may be expressed so:

$$W = 5.5 \times 10^{-12}T^3\Delta T \text{ calories/sec./cm}^2. \tag{48}$$

Thus, owing to the fact that the absolute temperature enters the expression to the third power, we see that the importance of radiation as an agency for heat transfer becomes greater at higher temperatures, until finally, in comparison, ordinary conduction becomes negligible.

At extremely high temperatures, the action of an insulator is the same as the action of a radiation baffle or series of baffles. The effect of baffles can be illustrated by the example of two infinite plane-parallel black surfaces at temperature T_1 and T_2. If a thin black baffle is interposed between these two surfaces, the transfer by radiation is reduced to one-half its original value. Two baffles reduce it to one-third, three baffles to one-fourth, and so forth, and if, instead of black baffles, polished metal reflectors are used, the insulation effect is even greater. In high-temperature furnaces the furnace tube with its winding is frequently surrounded by a thin sheet of some metal like molybdenum to serve as a baffle to reflect back most of the radiant energy emitted by the tube and so to decrease the power required. Sometimes, too, a second refractory furnace tube may surround the first to act as an insulator.

Low temperatures. Moderately low temperatures are obtained in the laboratory by immersion in baths of ice, salt and ice, dry ice, liquid air, and so forth. The various temperatures so attained are listed in Table IV. For obtaining

extremely low temperatures, the methods required are very elaborate.[6]

TABLE IV

FREEZING MIXTURES AND CONSTANT-TEMPERATURE COOLING BATHS

Bath		T (°C.)
NaCl, 33 parts, plus snow, 100 parts		– 21.3
$CaCl_2 + 6H_2O$, 100 parts, plus snow, 70 parts		– 54.9
Liquid nitrogen	Boiling point	– 195.8
Liquid oxygen	Boiling point	– 183
Solid CO_2	Sublimation point	– 78.5
Mercury	Melting temperature	– 38.9

Methods of obtaining high temperatures. *Flames.* The use of flames affords the most simple and convenient means of obtaining high temperatures.

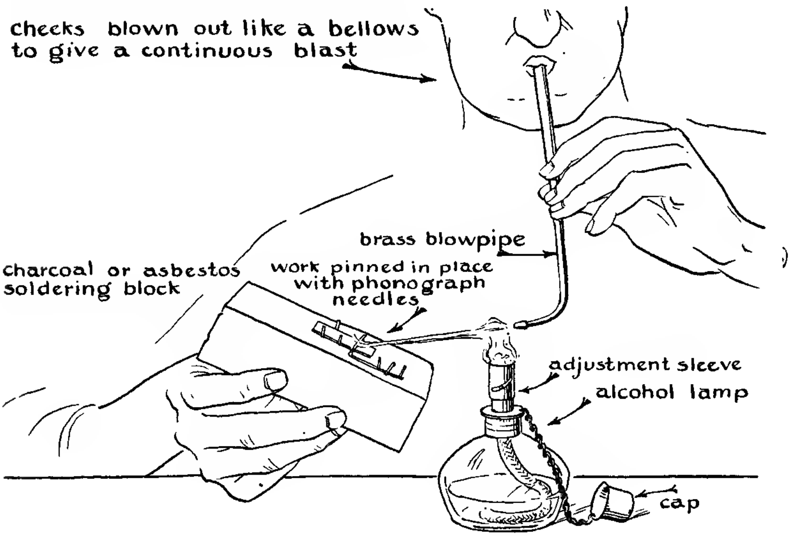

Fig. 4.

Fig. 4 illustrates the use of a blowpipe with the alcohol lamp, showing how the cheeks are used as bellows to give continuous air pressure.

[6] Meissner, W., *Handbuch der Physik*, Vol. 11, Chapter 7. Berlin: Julius Springer, 1926.

Fig. 5 illustrates the ordinary Bunsen burner. The Bunsen burner is simply a tube arranged with a fuel gas jet in the bottom and air ports in the sides near the bottom. It draws air in through these ports by injector action of the gas jet. The air drawn into the tube at the bottom is mixed with the fuel gas as it passes up through the tube; and above the top of the tube this air reacts chemically with the gas fuel to produce the flame.

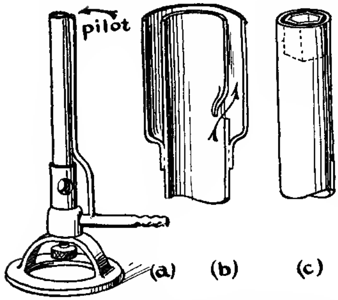

Fig. 5. Pilot attachment (b) is obtainable from the Forster Manufacturing Company, 2916 Otis Street, Berkeley, California, and attachment (c) is obtainable from the Central Scientific Company, Chicago, Illinois.

The Bunsen burner draws only about half as much oxygen through its ports as is required for burning the fuel. If more air were mixed with the gas, the velocity of propagation of the flame would be greater than the upward velocity of the gas in the tube, and the flame would "backfire." However, additional air required for combustion of the gas is supplied to the flame above the burner tube; owing to the more abundant supply of air, at the edges of the flame the propagation velocity is greater than the upward velocity of the gas, so that the fire does not blow itself out.

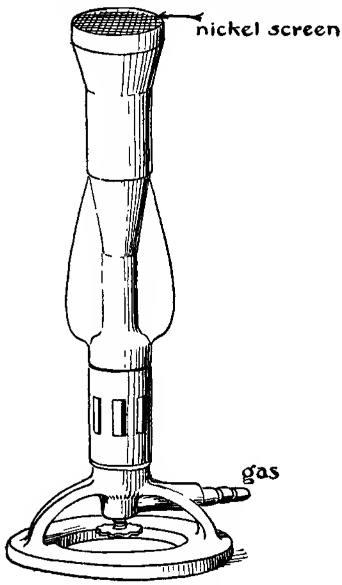

Fig. 6.

Natural gas, which contains less hydrogen than coal gas, has a much smaller flame velocity. (The heat of combustion and the chemical composition of some commercial fuel gases

TABLE V

COMMERCIAL FUEL GASES

Gas	B.t.u. per Cubic Foot	Per Cent H_2	Per Cent CO	Per Cent Methane and Ethane	Per Cent Propane and Butane
Coal gas.....	527	58	6	27	0
Natural gas..	1100	0	0.1	89	2
Bottled gas..	3037	0	0	0	100

Central Scientific Company Catalogue.

are shown in Table V.) Accordingly, with natural gas there is a greater tendency of the burner to blow out than with coal gas. This has resulted in the invention of fixtures like those shown in Fig. 5(b) and (c), which serve to retard the upward velocity of a portion of the gas mixture. The flame formed by this slowed-up portion does not blow out, and it prevents the main flame from doing so. A small tube may be soldered to the burner as shown in Fig. 5 at (a) to act as a pilot as well as to prevent the flame from blowing out.

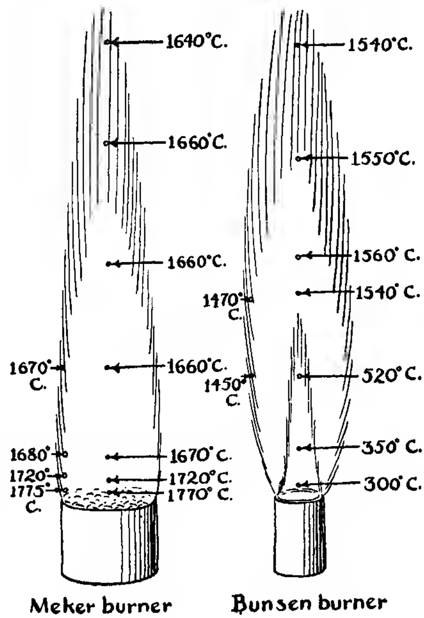

Fig. 7. After F. Haber.

The Meker burner is a Bunsen-type burner with the top of the burner tube flared out and fitted with a nickel grill. This is illustrated in Fig. 6. The Meker burner can burn coal gas with a higher air admixture than the Bunsen burner, because the grill, acting as a Davy lamp screen, prevents

the flame from backfiring. The hot inner blue cone of the Bunsen flame is replaced here by an array of small cones,

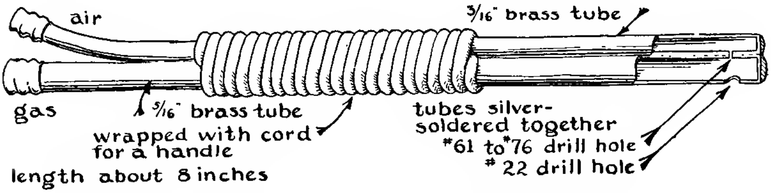

Fig. 8. After Ernst von Angerer.

one over each element of the grill. This array produces a flame which is both hotter and more uniform over an extended area than the Bunsen flame. The temperature distributions in the Bunsen and Meker flames, with coal gas fuel, are shown in Fig. 7.

To obtain a higher temperature than either the Bunsen or Meker will yield, the fuel is burned with air or oxygen under

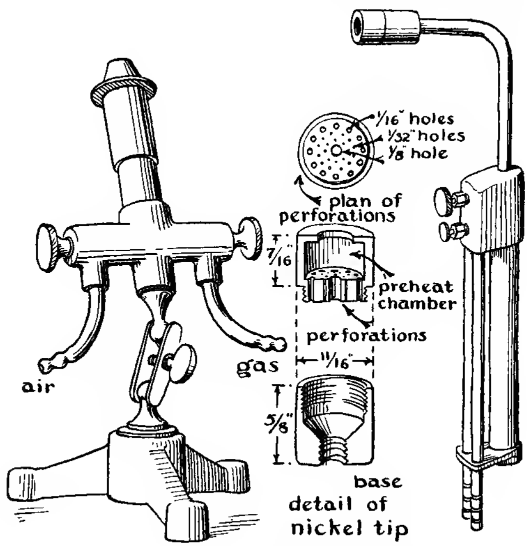

Fig. 9. The burner shown at the right, for natural-gas fuel, is obtainable from the Forster Manufacturing Company, 2916 Otis Street, Berkeley, California.

pressure at the end of an orifice with burners such as the ones shown in Figs. 8 and 9. When natural gas is burned

with air, a special tube end is required. (See Fig. 9.) Another method of burning gas to get a high temperature is to

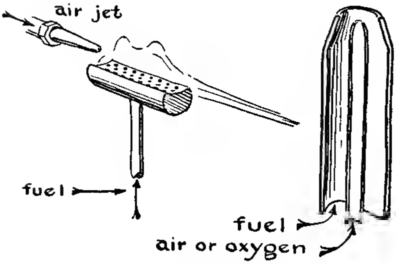

Fig. 10.

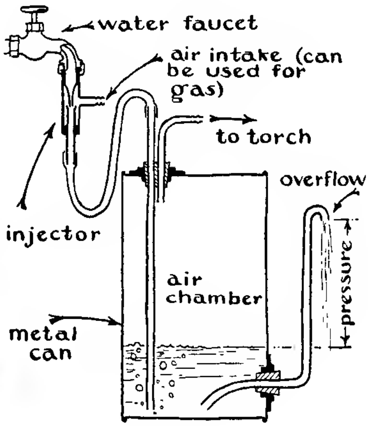

Fig. 11.

project a jet of air or oxygen through a gas flame as shown in Fig. 10. A simple method using a water aspirator for obtaining compressed air at moderate pressures is shown in Fig. 11.

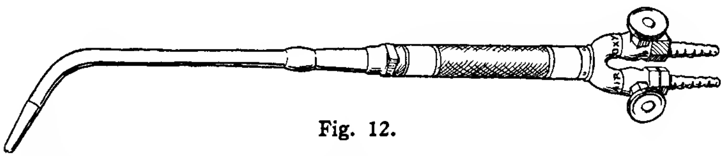

Fig. 12.

Extremely high temperatures are attained with oxyhydrogen or oxyacetylene torches. Commercial torches like the one illustrated in Fig. 12 are recommended for these fuels.[7] These torches are equipped with a mixer, usually in the handle, to produce a homogeneous solution of the fuel and oxygen gases. It is very important to have such a homogeneous mixture of oxygen and fuel;

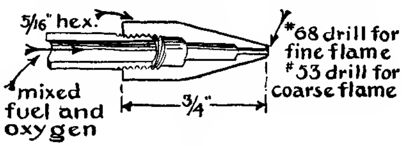

Fig. 13.

[7] These torches are obtainable from the Linde Air Products Company, 30 East 42nd Street, New York City.

otherwise the torches would blow themselves out. The type of orifice used is illustrated in Fig. 13. Fig. 14 shows the distribution of temperature in the oxyacetylene flame and also in the carbon arc.[8]

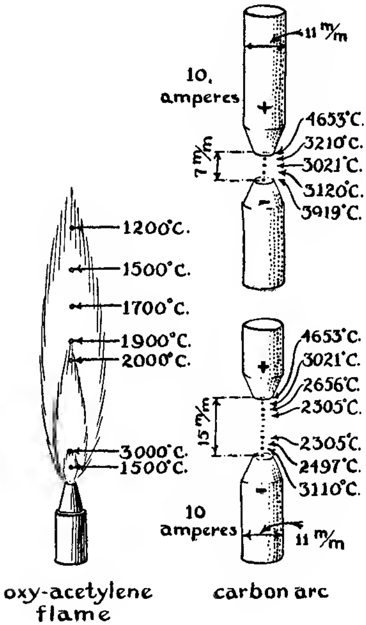

Fig. 14.

A furnace is required to heat objects to higher temperatures than those that are obtainable with torches. Gas furnaces for use in the laboratory are shown in Figs. 15 and 16.

Oxygen-gas furnaces can be made to yield very high temperatures; for example, Podszus and von Wartenburg, Linde, and Jung have described furnaces with a zirconium dioxide tube using illuminating gas or oil vapor as fuel.[9] These furnaces attain temperatures of about 2600°C.[10]

Electric furnaces. Electric furnaces for temperatures to 500°C., useful for such applications as the baking out of charcoal traps, can be made by winding a coil of Nichrome or Chromel wire on an iron tube as shown in Fig. 17. The

---

[8] Flame and carbon-arc temperature:

Kautny, Th., *Leitfaden für Azetylenschweisser*, page 86. Halle: Marhold, 1925.

Mathiesen, W., *Untersuchungen über den elektrischen Lichtbogen.* Leipzig: Haberlandt, 1921.

[9] Podszus, E., *Zeit. für angew. Chem.*, *30*, 17 (1917), *32*, 146 (1919).

von Wartenburg, H., Linde, H., and Jung, R., *Zeit. für anorg. u. allgem. Chemie*, *176*, 349 (1928).

[10] For treatment of high-temperature refractories see Swanger, W. H., and Caldwell, F. R., *Bureau of Standards J. of Research*, *6*, 1131 (1931).

Many of the high-temperature refractories are obtainable from the Foote Mineral Company, Philadelphia, Pennsylvania.

See Langmuir, I., "Flames of Atomic Hydrogen," *Indust. and Engin. Chem.*, *19*, 667 (1927).

tube is first covered with a piece of mica or asbestos sheet to avoid shorting out the winding. A simple way of fastening the ends of the winding is illustrated in Fig. 18. Various

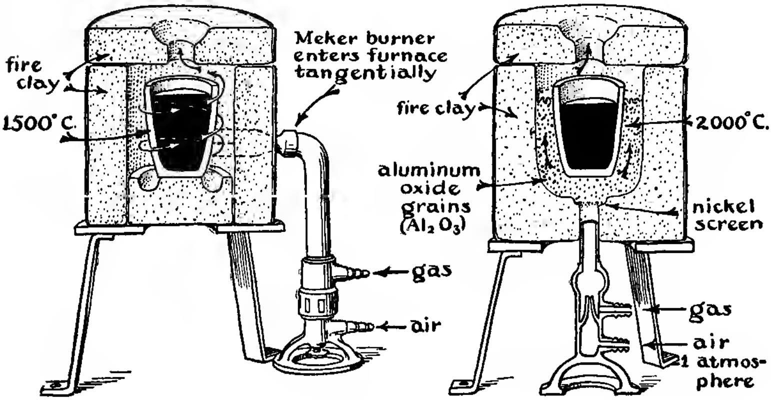

Fig. 15.

types of insulation may be used. For example, the inner tube and its resistance wire winding may be covered with several layers of asbestos. The furnace is assembled with transite[11] ends, using Insa-lute cement. It is necessary to avoid contact between the Insa-lute cement and the furnace wire at elevated temperatures.

Nickel wire is suitable for a furnace winding. However, its resistance changes approximately twofold when it is heated from room temperature to 500°C. This behavior is in contrast to the behavior of the nickel-chromium alloys,

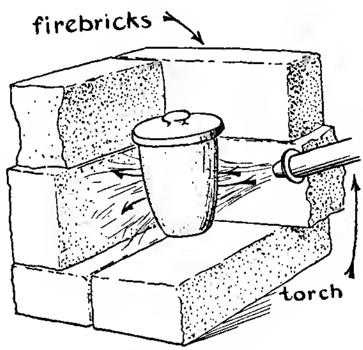

Fig. 16. An improvised furnace.

[11] Transite is an asbestos fiber and Portland cement mixture formed under high pressure into dense, monolithic sheets of high strength, rigidity, and durability. It may be purchased from the Johns-Manville Corporation, 22 East 40th Street, New York City.

whose change of resistance is negligible. The change of resistance of nickel may or may not be desirable; it may be desirable to have a large coefficient if the resistance is to be used for regulating the temperature of the furnace.

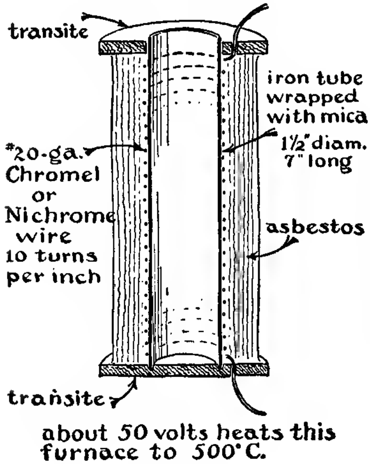

Fig. 17.

Electric furnaces which operate in air to 1100°C. may be made with the nickel-chrome alloys as resistors, a porcelain, Alundum, quartz, or magnesia tube being used to support the winding. Diatomaceous earth makes an excellent insulator.[12] A useful furnace construction for the laboratory is illustrated in Fig. 19.

Platinum may be used as resistor for temperatures greater than 1100°C., when it is desired to have the furnace operate in air. This resistor will operate up to a temperature limit of 1600°C. In order to obtain a furnace temperature as near this limit as possible, Orton and Krehbiel used a Chromel "booster" winding on a tube mounted outside of and concentric with the platinum winding.[13] The platinum wire may be wound on quartz glass, which has a temperature limit in air of 1300°C., on unglazed porcelain, for which the limit is 1400°C., or on clay, with a limit of 1700°C. However,

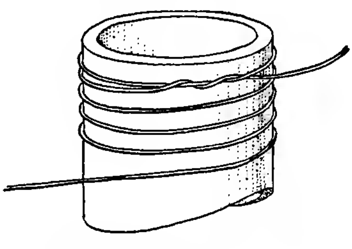

Fig. 18.

[12] This may be obtained from Johns-Manville under the trade name Sil-O-Cel. The calcined diatomaceous silica comes as a coarse granular material and as molded insulating bricks.

[13] Orton, E., Jr., and Krehbiel, J. F., *Amer. Ceramic Soc., J., 10,* 375 (1927).

best of all is an Alundum tube (alumina with clay binder). Its limit, 1900°C., is above that of the platinum.

Silicon is formed from quartz or porcelain in a reducing atmosphere, and silicon attacks platinum. Accordingly, it is best to use a platinum-wound furnace in an oxidizing atmosphere. If, however, the wire is wound on an Alundum tube, it may be operated in a reducing atmosphere.

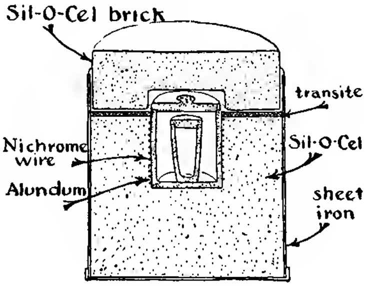

Fig. 19.

Molybdenum or tungsten can be used as a resistor in an atmosphere of hydrogen; the limiting temperatures attainable are 2200°C. and 3000°C. respectively. As a support for the resistor winding, Alundum can be used to 1900°C., magnesia to 2200°C., zirconia to 2500°C., and thoria to

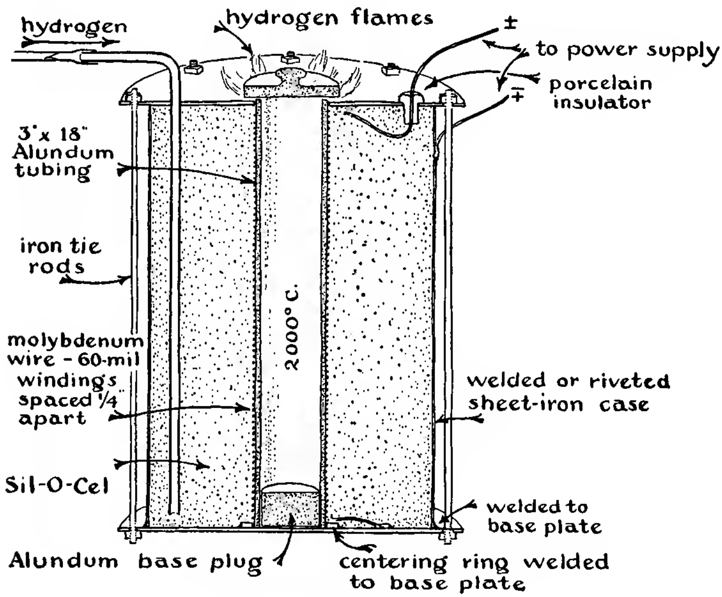

Fig. 20. Hydrogen furnace.

3000°C. Porcelain is unsuitable, for the reason given above; namely, hydrogen blackens it at high temperatures.[14] A tungsten (or molybdenum) furnace is shown in Fig. 20. Most refractories cannot be subjected to high temperatures

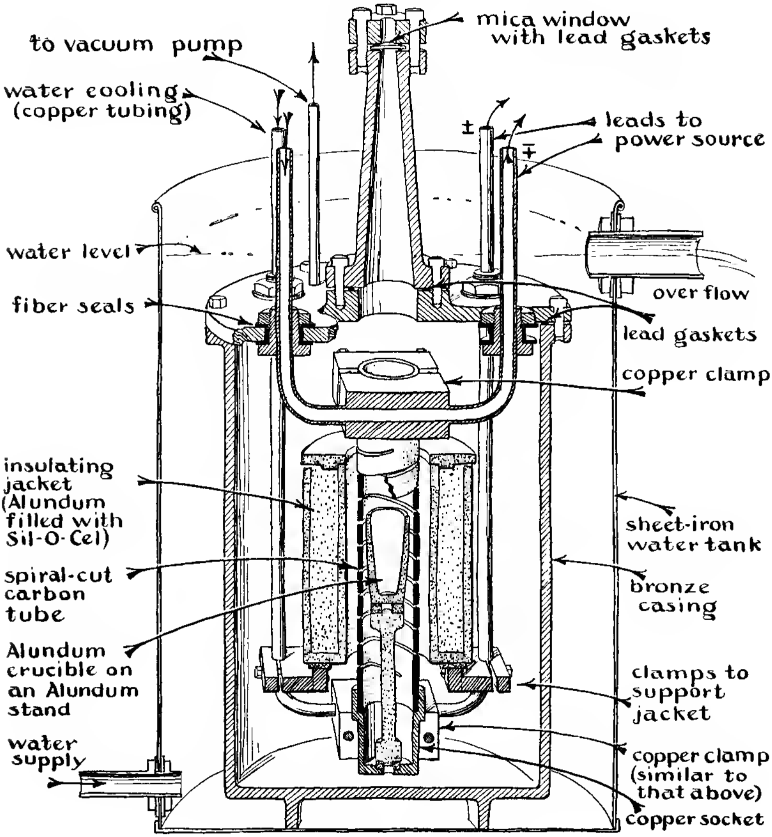

Fig. 21. The Arsem furnace.

in vacuum because they either evaporate or are reduced by the vacuum (oxygen formed by dissociation is pumped away).

Carbon and graphite tube furnaces can be operated to a

[14] For tables of physical and chemical properties of refractories see Hougen, O. A., *Chem. and Met. Eng.*, *30*, 737 (1924).

temperature of 2000°C. in vacuum. Above this temperature the carbon begins to vaporize, and at 2500°C. the rate of evaporation is rapid. In hydrogen or nitrogen the temperature limit is 2000°C. At this limit chemical action between the carbon and the gas sets in. However, in an atmosphere of carbon monoxide, carbon resistors may be used at temperatures over 3000°C. A furnace designed by Arsem,[15] which may be operated either in an atmosphere of carbon monoxide or in vacuum, is shown in Fig. 21. This furnace has its resistor tube cut into a spiral to increase its resistance and flexibility. Connections are made to the ends of the resistor tube with water-cooled copper jaws.

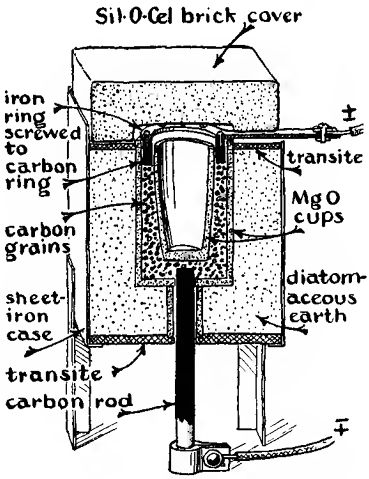

Fig. 22.

Carbon grain resistors such as the one shown in Fig. 22 have a higher electrical resistance than solid carbon and are often useful in the laboratory.

A carbon-arc furnace is shown in Fig. 23.

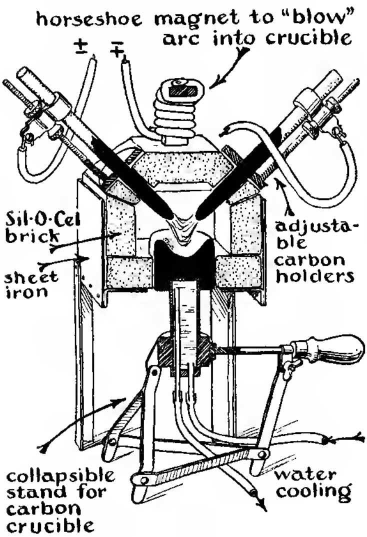

Fig. 23. After W. Schuen.

Fig. 24 shows apparatus used for melting metals in vacuum by heating with high-frequency current. It is peculiar to this method that the metal charge is at a higher temperature

[15] Arsem, W. C., *Am. Electrochem. Soc., Trans.*, *9*, 153 (1906).

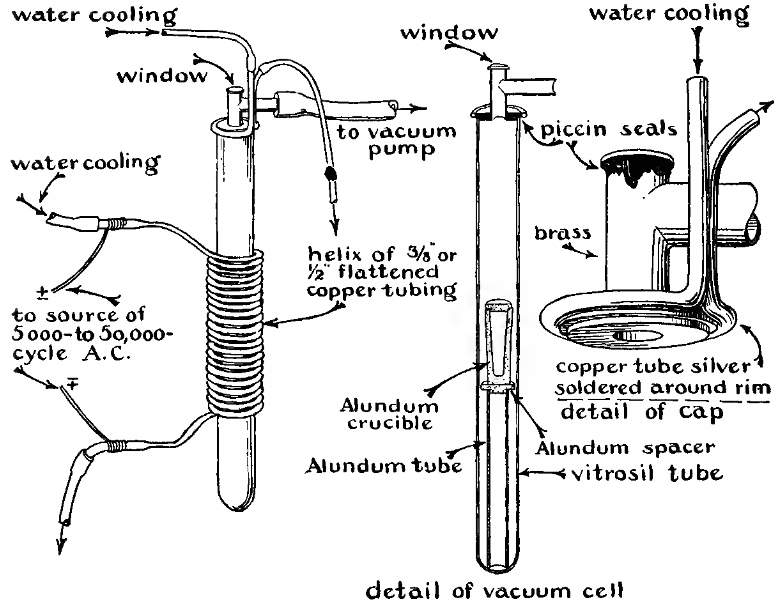

Fig. 24. Apparatus for melting metals in vacuum with high-frequency currents.

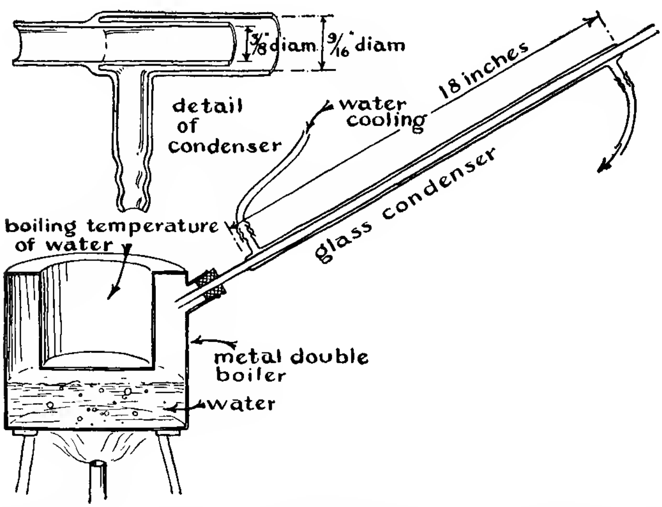

Fig. 25. Air bath. A Liebig condenser with a narrow cooling chamber is most efficient.

than the crucible, a fact of practical value when working with extremely refractory metals.[16]

Fixed temperatures. Constant temperature may be maintained at 0°C. with melting ice, and at the boiling temperature of water by means of a device such as the one illustrated in Fig. 25. Other liquids and solids may be used for maintaining other constant temperatures; for example, a temperature of 444.6°C. is obtained by boiling sulphur. Some of the fixed temperatures useful for the calibration of thermometers and thermocouples are given in Table VI.

TABLE VI

STANDARD TEMPERATURES

Bath	T(°C.)
Carbon dioxide (sublimation temperature)	− 78.51
Mercury (melting temperature)	− 38.87
Ice (melting temperature)	0
$Na_2SO_4 \cdot 10H_2O$ (transition temperature)	32.38
$MnCl_2 \cdot 2H_2O$ (transition temperature)	50.09
Steam condensation (at 760 mm pressure)	100
Naphthalene (boiling temperature)	217.96
Tin (melting temperature)	231.84
Benzophenone (boiling temperature)	305.9
Sulphur (boiling temperature)	444.6

Thermostatic devices. Here we cannot treat all of the many devices described in the literature for controlling the temperatures of furnaces and thermostatic baths.[17] How-

[16] Northrup, E. F., *Frank Inst., J.*, *195*, 665 (1923).

Equipment for high-frequency heating is obtainable from the Ajax Electrothermic Corporation, Trenton, New Jersey.

[17] Haagn, E., *E. T. Z.*, *40*, 670 (1919).

Haughton, J. L., and Hanson, D., *Engineering*, *104*, 412 (1917).

Haughton, J. L., *Journ. Sci. Instruments*, *9*, 310 (1932).

Roberts, H. S., *J. O. S. A.* *6*, 965 (1922).

White, W. P., and Adams, L. H., *Phys. Rev.*, *14*, 44 (1919).

The Fish-Schurman Corporation is United States agent for German thermostats covering the temperature range − 35°C. to 300°C.

See also the following:

Beattie, J. A., *Rev. Sci. Instruments*, *2*, 458 (1931).

Roebuck, J. R., *Rev. Sci. Instruments*, *3*, 93 (1932).

Concerning the use of the thyratron for temperature control see the following:

Hull, A. W., *Gen. El. Rev.*, *32*, 213, 390 (1931).

Zabel, R. M., and Hancox, R. R., *Rev. Sci. Instruments*, *5*, 28 (1934).

Zabel and Hancox were able to get a constant temperature of 880°C. ± .06°.

ever, the principle on which they operate is the same, namely, the balancing of the heat input to the furnace against its heat losses. The heat input is controlled by a pilot indicator which is continually kept oscillating about a mean position corresponding to the desired temperature. When it is on either one or the other side of the mean position, it modulates the heat input: When the pilot indicates the temperature low, the heat input is automatically increased, and when it indicates high, the heat input is diminished. In this sense one does not maintain a constant temperature but a periodic one which varies between more or less fixed limits about a mean temperature.

As an example of a temperature-regulating device, let us consider a furnace with its winding made one arm of a self-balancing Wheatstone bridge, the bridge current in this arm serving at the same time as furnace heating current. The furnace winding must be made of nickel, molybdenum, tungsten, or platinum for this type of regulator, since the nickel-chromium alloys do not have a suitable temperature coefficient of resistance. The other resistances in the Wheatstone bridge may be rheostats made from a low-temperature-coefficient alloy such as constantan. The bridge galvanometer serves as the pilot to control the heating current.

Let us compare this method with one which employs a thermocouple inside the furnace as a pilot. We see that there will be more lag between the time the heat input is altered and the time it affects the thermopile. As a result, with the thermocouple pilot the limits of the fluctuation of the furnace temperature are separated more than they are when the resistance of the heater wire serves as the pilot.

Even when the furnace heater wire serves as the pilot, there are fluctuations due to the period of auxiliary instruments. These temperature fluctuations may be diminished simply by interposing alternate shells of thermal "ballast" and insulator between the furnace winding and the region that is to be kept at a constant temperature. The tempera-

ture diffusion through such alternate shells is slow. The furnace tube itself, which separates the heater wires from the constant temperature region within, is usually adequate for this, because of its relatively low diffusivity, h; for example, one may obtain temperatures constant to about

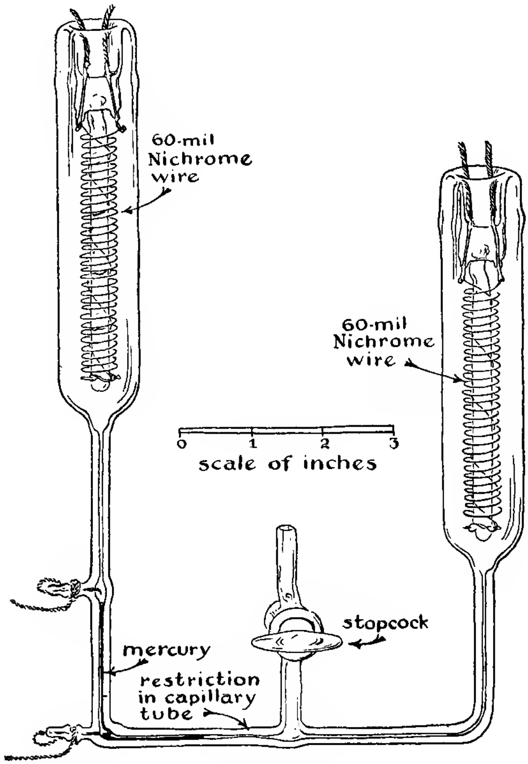

Fig. 26.

0.01°C. inside the furnace tube even when the period of temperature oscillation of the furnace wiring outside is of the order of 30 seconds.

The device shown in Fig. 26 is convenient for temperature regulation.[18] The two bulbs of this device have equal volumes, and they are equipped with identical nickel-

[18] Proctor, R. F., and Douglas, R. W., *Journ. Sci. Instruments*, *9*, 192 (1932).

chromium alloy heaters and connected electrically as shown in the diagram, Fig. 27. The bulbs are filled with air and the pressures on either side of the mercury column are such as to hold the top surface of the mercury at the level of the tungsten contact when the voltage drop over the left resistance (see Fig. 26) is the same as the voltage drop over the right resistance. These voltage drops are equal when the temperature-sensitive feeler resistance is the same as the fixed constantan resistance. (See Fig. 27.) These resistances are adjusted to be equal at the desired temperature. If the temperature of the feeler resistance is too high or too low, the heating in the two bulbs is unequal, and the resulting change in pressure in the bulbs opens or closes the mercury contact, and this in turn operates a relay actuating the heating and bridge current.[19]

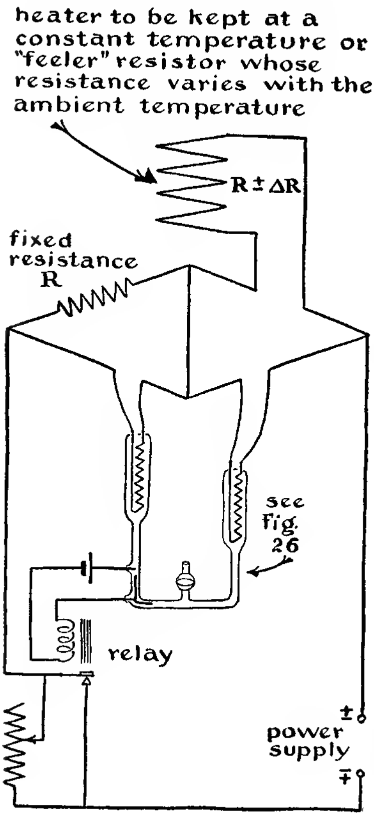

Fig. 27.

The resistance used to operate the regulating device may be either the heater resistance or it may be separate from the heater. In the latter case this arrangement is suitable for maintaining a constant temperature in a room. The feeler resistance is strung back and forth near the ceiling of the

[19] Mercury thermoregulators, relays, and electric bath heaters are handled by American Instrument Company, 774 Girard Street, N. W., Washington, D. C.

room (at about 8 feet above the floor). For such an application the heaters, which the regulating device controls, are situated in front of the ventilator air inlet to the room.

Thermostat baths use water for ordinary temperatures, oil or eutectic salt mixtures for elevated temperatures, and alcohol for low temperatures. Beattie gives the composition of two eutectic baths. (See Table VII.) These baths are useful in the temperature range above 120°C. The lower limits of their temperature ranges overlap the upper temperature limits of mineral-oil baths (150° to 200°C.) and heavy cylinder oil baths (150° to 300°C.).

The temperature of a water bath is controlled by regulating the heat input. A mercury-in-glass bulb with contacts coupled to a relay as shown in Fig. 18, Chapter X, is suitable for a bath heated electrically. The device shown in Fig. 28 is effective for controlling the temperature of a gas-heated

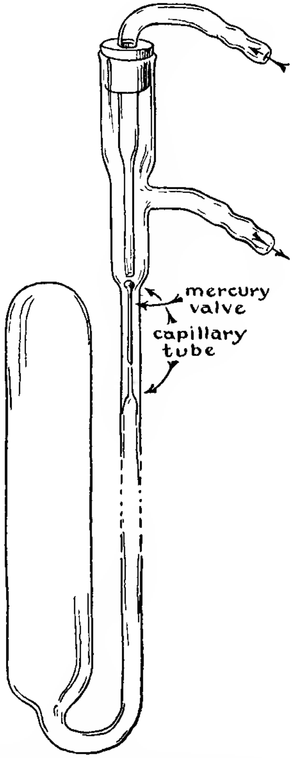

Fig. 28. After W. Ostwald.

TABLE VII

HIGH-TEMPERATURE BATH FLUIDS

Bath	T(°C.)
Mineral seal oil	200
Heavy cylinder oil	150 to 300
30% $LiNO_3$ by weight 14% $NaNO_3$ by weight 56% KNO_3 by weight	120 to 500

Beattie, *Rev. Sci. Instruments*, *2*, 458 (1931).

bath. The aperture through which the gas for the flame passes is regulated by the thermal expansion and contraction of the mercury. With these devices the fluctuations of the bath are about 0.1°C.

Temperature measurement. Temperature is always measured practically by a measurement of some temperature-sensitive property, such as light emission, electrical resistance, length, volume, thermal e.m.f., and so forth. All physical properties which vary with temperature are possibilities for such a measurement, although some properties, like electron emission, are so strongly influenced by chemical impurities or by the past physical history of the thermometric substance that they are useless.

Liquid-in-a-bulb thermometers depend upon change of volume with temperature for their readings. Among them, two are of unusual interest. One, which was manufactured in Germany at one time, used gallium as liquid and fused quartz for the bulb and capillary. This thermometer was useful up to a temperature of about 1000°C., in contrast to the mercury thermometer, which is ordinarily useful only to 200°C. However, with a high pressure of nitrogen (up to 40 atmospheres) mercury-in-glass thermometers may be heated considerably above 200°C. A graphite thermometer with molten tin as the liquid has been made by Northrup.[20] This thermometer may be used to 1680° without chemical reaction between the tin and the graphite. As tin does not boil at 1680°C., Northrup thinks that the limit in temperature of this thermometer is probably several hundred degrees higher. The position of the tin in the graphite capillary is determined by a tungsten feeler. For gallium the temperature range from the melting point to the boiling point is from 29.7° to 1600°C., and for tin it is from 231.8° to 2260°C. The operation of the two thermometers described above depends upon these unusually long temperature intervals between the melting points and boiling points.

[20] Northrup, E. F., *Pyrometry*, page 464. New York: published by the Am. Inst. of Mining and Metallurgical Engineers at the office of the secretary, 1920.

Thermocouples operate by virtue of the temperature dependence of the thermal e.m.f. generated by two substances in contact. The thermocouple may be employed in the laboratory for temperature measurement from liquid air temperatures to the melting temperature of molybdenum.

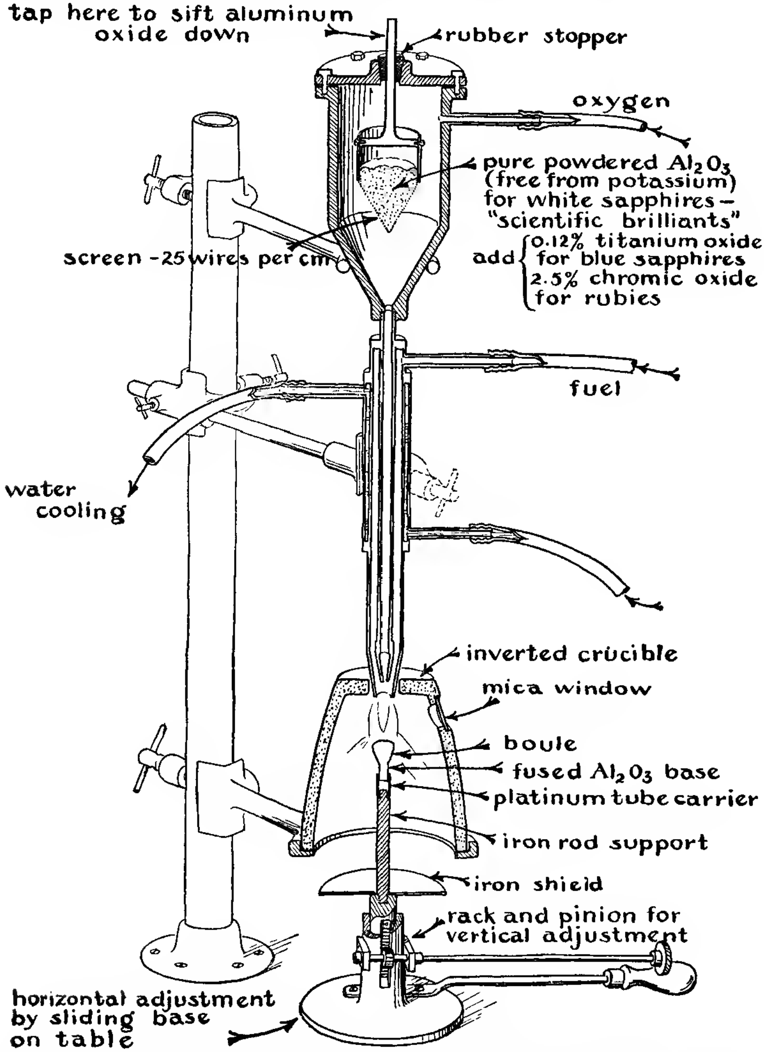

Fig. 29. Verneuil's arrangement for making artificial rubies and sapphires. Verneuil, A., *Ann. de Chemie et Physique, 3,* 20 (1904).

The base metals commercially available are commonly used as thermoelectric wires. Chromel-Alumel wires have a high coefficient of thermal e.m.f. They are obtainable from the factory matched to give the temperature to $\pm$ 5°C. Copper and constantan wires also have a high thermal e.m.f. These wires have the advantage over Chromel-Alumel that they are easily soldered. The LeChatelier combination (platinum and 10 per cent platinum-rhodium) is used for precision measurements. Special thermocouple metals, such as tungsten, molybdenum, and their alloys, are useful at very high temperatures.

It may be desired to calibrate a particular thermocouple with fixed standard-temperature baths such as those listed above in Table VI. The best procedure is to use the calibration curve supplied by the factory, which gives the e.m.f. at frequent temperature intervals, and to plot an empirical correction curve for it from the calibration data.

Radiation pyrometers determine temperature by the measurement of light emission. There are several types, and descriptions of them and their operating characteristics appear in many books. The type in most common use measures, with a special photometer, the intensity of monochromatic light (6600 Å) emitted by the incandescent body whose temperature is being measured.

Table VIII is useful for estimating the temperature of a body from its color.

TABLE VIII

COLOR TEMPERATURES

Color	Approximate Temperature (°C.)
Incipient red heat	500 to 550
Dark red heat	700
Bright red heat	900
Yellowish-red heat	1100
Incipient white heat	1300
White heat	1500

CHAPTER XIII

Notes on the Materials of Research

Alkali metals. One of the alkali metals may be required for the sensitive surface of a photocell or as a thin-film filter for ultraviolet light; or in the vapor phase the metal may be used for the demonstration of the phenomenon of resonance radiation. For these and other applications we will outline, briefly, some of the ways of manipulating these very reactive metals.

The alkali metal may be prepared from the alkali chloride, reduced with calcium metal in an evacuated glass tube:

$$2M\mathrm{Cl} + \mathrm{Ca} \rightarrow \overline{2M} + \mathrm{CaCl_2}. \quad (1)$$

The reaction progresses in the indicated direction at elevated temperatures on account of the removal of the free alkali metal, M, by evaporation. This reaction may be varied: A chromate of the alkali metal may be used instead of the chloride, and zirconium metal may be used instead of calcium. The reaction applies to the preparation of all the alkali metals, with the exception of lithium, which reacts with the glass or quartz; lithium is best reduced from its chromate with zirconium metal in an iron apparatus.

We will consider, in detail, how potassium may be prepared by the reaction indicated in Eq. 1. Pulverized potassium chloride and calcium metal filings are mixed together in a closed-end iron tube in stoichiometrical proportions (3.7 g KCl to 1 g Ca). This iron tube is introduced into the thickened end of a hard-glass tube as shown in Fig. 1. The glass is thickened in order to allow the attainment of the maximum temperature; at lower temperatures where a thinner glass wall would collapse the reaction pro-

ceeds very slowly. After the iron tube is introduced, the hard-glass tube is closed by fusing the glass with the hand torch. After a good vacuum is attained, the chemicals are heated, slowly at first and finally strongly until the reaction is complete. The chemicals may be heated until the glass starts to soften, but too much heat should be avoided, since it will distill calcium metal. The reduced and once-distilled metal condenses in the bend of the tube as shown in Fig. 1. From there, it is worked down with the flame into the receiving ampoule, where it is sealed off as illustrated.

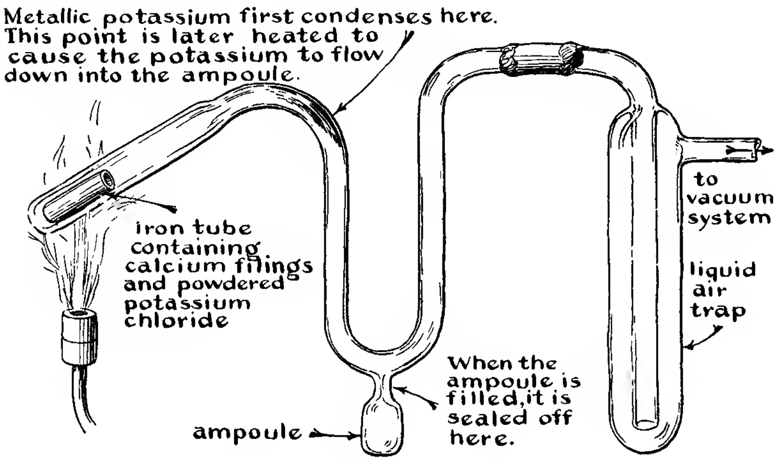

Fig. 1.

The alkali metals react vigorously with air, and the ampoule should be opened without exposing the metal to air. This is done by the following procedures: The ampoule is constructed of Pyrex glass with an annular tungsten ring to spring the glass. After the ampoule is mounted in the vacuum system, the tungsten ring is heated with a high-frequency induction coil until the glass breaks. (See Fig. 2.)

A scheme which does not involve the use of high-frequency heating but which breaks the glass by impact is illustrated by Fig. 3. The illustrated depression in the tube wall acts as a safety to confine the armature and prevent accidental

fracture of the ampoule until the apparatus is sealed onto the high-vacuum system. During this sealing operation the depression is blown out of the way of the armature. The armature is operated in the vacuum, by means of an external electromagnet, to break the tip of the ampoule, thus exposing the alkali metal. The tip may be scratched with a file to facilitate breaking.

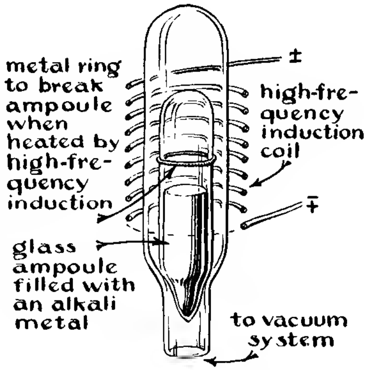

Fig. 2.

The ampoule may be cooled in a beaker with dry ice in the bottom and carbon dioxide vapor above. The tip is opened under the surface of the carbon dioxide vapor. The ampoule is then quickly transmitted to the vacuum system, sealed in, and evacuated. The expansion of carbon dioxide in the ampoule through the tip prevents access of air to the alkali metal.

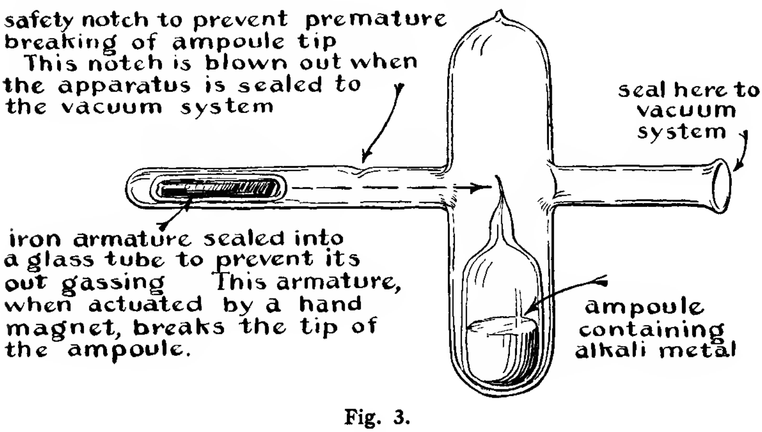

Fig. 3.

The alkali metals, as obtained commercially in small cubes or irregularly shaped pieces, are packed submerged under kerosene. The metal may be cleaned and manipulated as

follows:[1] First the metal is washed in dried petroleum ether or benzene to free it from kerosene. The petroleum ether or benzene is dried by shaking it in contact with calcium chloride. (Carbon tetrachloride or chloroform should not be used to wash the metal, since an explosive compound is formed.) The metal is then fused in the bottom of an 8-mm glass tube and sucked up into a 1-mm capillary glass tube with a rubber hose. This 1-mm tube is sealed off with a flame just above the metal. At the other end the alkali is protected from the air by soft wax. A suitable length of this composite

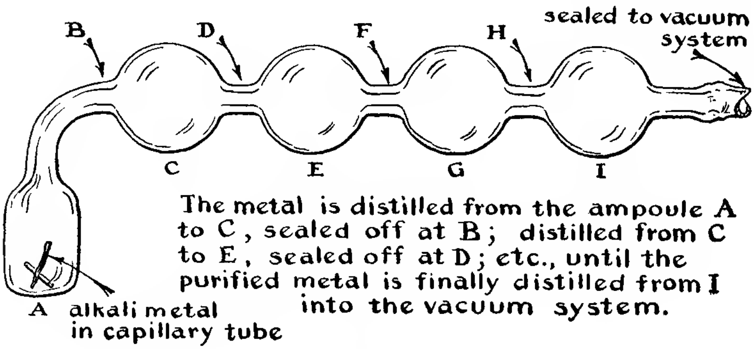

Fig. 4.

glass-metal rod may be cut off with wire cutters and introduced into a distilling bulb fastened to the vacuum system where the metal is desired. (See Fig. 4.)

A distillation procedure[2] for sodium metal is illustrated in Fig. 5 whereby the metal is refluxed under vacuum to free it of hydrogen and carbohydrates (the hydrogen contained in potassium or sodium, measured as a gas at atmospheric pressure, may amount to one or two hundred times the volume of the metal). The metal cubes are washed to free them of kerosene, as described above, and then they are introduced into Chamber I. After the whole system is evacuated, the metal is fused in this chamber. Chamber I acts as a separating funnel. The fusion is accomplished by the

[1] Wood, R. W., *Phys. Rev.*, *44*, 353 (1933).
[2] I am indebted to Dr. Carl F. J. Overhage for this procedure.

application of a soft flame, so that the metal runs into Chamber II, leaving the dross behind. Chamber I is then removed at the seal-off. The metal is heated in Chamber II with a small electric furnace. Here it is refluxed for several

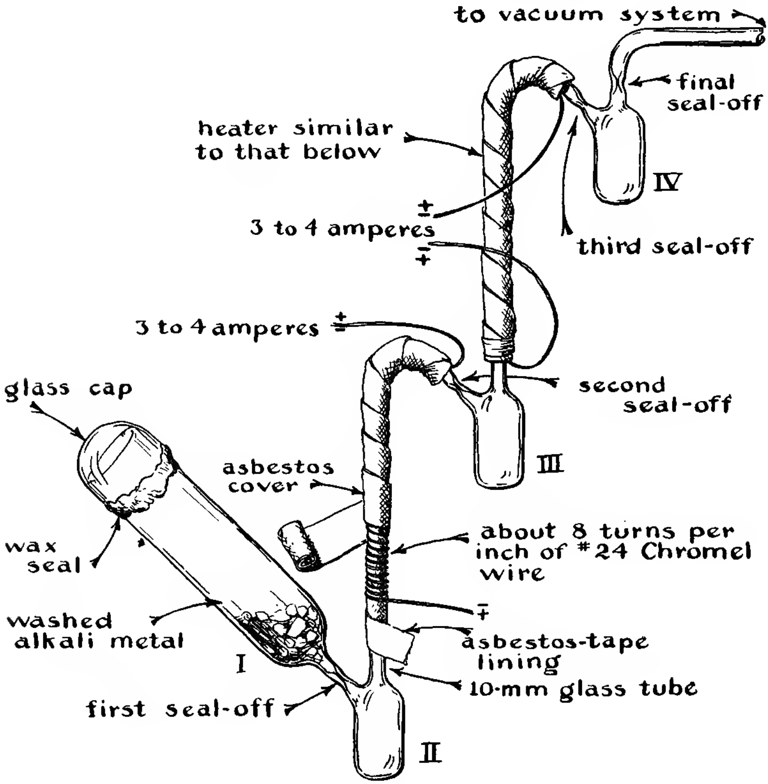

Fig. 5.

hours. The distilled metal condenses in the asbestos-insulated tube above Chamber II. This refluxing allows hydrogen and hydrocarbon vapors to be pumped away. After this treatment the metal is distilled into Chamber III by a heater wire around the condenser tube. Chamber II is then removed at the seal-off. Chamber III may be the receiver for the metal, or it may be further refluxed and distilled into a final receiving ampoule. Electric heat is recommended for

distilling the alkali metal, since there is some danger of breaking the glass if it is heated with a torch.

In manipulating the alkali metals the following precautions should be observed: The amount of metal manipulated should never be greater than necessary. A box of sand should be at hand for the control of accidental fires. The alkali metals should never be allowed to come in contact with water. Used metal and apparatus containing the alkali

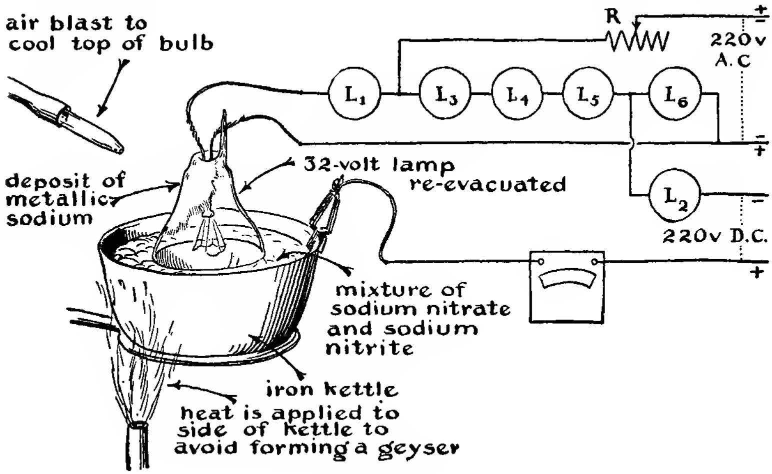

Fig. 6.

metals should be disposed of by burying only. It is advisable to wear goggles to protect the eyes while manipulating the alkali metals.

Sodium may be prepared by electrolysis through the soda-glass walls of an electric lamp. A 32-volt lamp, which has a larger tungsten filament wire than the 110-volt lamp, is best for this purpose. The lamp bulb is first evacuated by means of a side tube sealed on for this purpose. It is then dipped in a bath of fused sodium nitrate and nitrite and connected to a source of electrical energy as shown in Fig. 6. Current is carried from the tungsten filament to the glass walls of the lamp bulb by electrons or by means of a sodium discharge, or in special cases by means of an argon discharge. The

practical details of this procedure are due to Dr. R. C. Burt, who graphically described the procedure as one which allows the vacuum to be electroplated with sodium.[3] The free metal is formed from the reduced sodium ions (which migrate through the solid glass electrolyte when a current flows). These ions are reduced by electrons, or negative sodium (or argon) ions. Faraday's law applies to the electrolysis. The spectrum of the sodium vapor discharge has been photographed and the spectrum indicates high purity of the electrolyzed metal. Impurities were estimated by Dr. Burt as being present, at most, in the proportion of 2 parts per

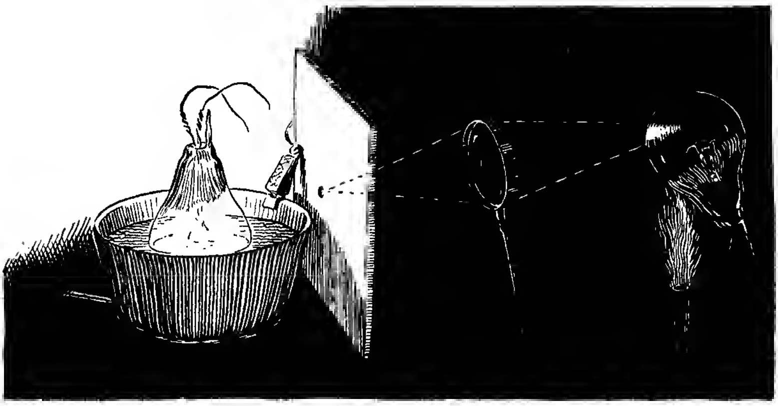

Fig. 7. Fluoresence of sodium vapor.

million. Sodium prepared by electrolysis is characterized by the fact that it is completely free of hydrogen and carbohydrates.

The electrolysis current varies from a few milliamperes when the current is carried entirely by electrons to a few hundred milliamperes when it is carried by sodium ions. The sodium discharge is obtained by simply removing the air blast on the lamp bulb which normally serves to keep the metal condensed.

Burt states that the spectrum from the sodium discharge is not reversed; a warmed lamp containing sodium will

[3] Burt, R. C., *J. O. S. A.*, *11*, 87 (1925).

fluoresce if the light of the sodium discharge from another lamp is focused on it. (See Fig. 7.)

Sodium may be introduced into quartz photocells by means of a graded seal as shown in Fig. 8.

Potassium can be electrolyzed through a potassium glass which is free of sodium and lead. A bath of fused potassium nitrite and nitrate is used.

The alkali metals potassium and sodium may be dissolved in the volatile solvent, liquid ammonia, and deposited where

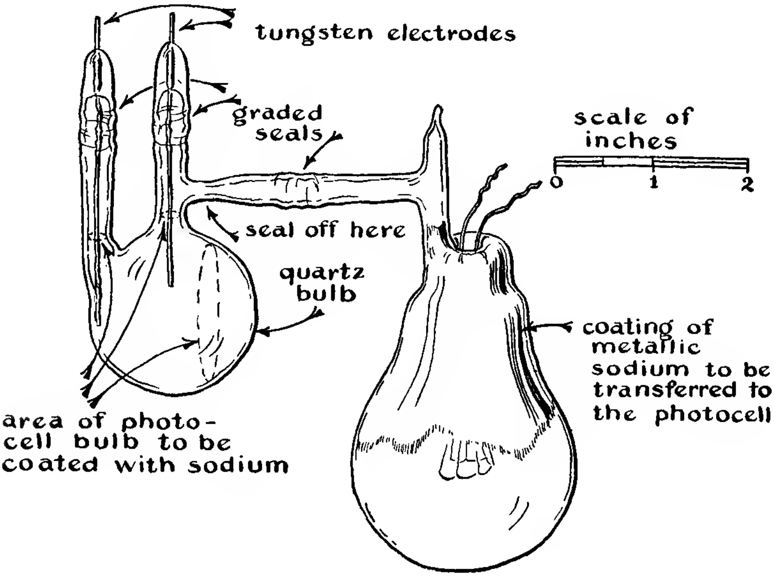

Fig. 8.

they are desired by boiling away this solvent. Lithium is managed in a similar manner with aethylamine as solvent.

All the alkali metals react with glass at elevated temperatures and especially with lead glass, with which they should not be allowed to come in contact.

The resistance of Pyrex-glass tubes toward sodium can be improved if they are lined with a film of borax or boracic acid. The tube to be lined is filled with a hot saturated solution of borax. The borax precipitates from this solution

as crystals on the inner glass walls of the tube as the solution cools. When the glass has become lined with a thin coating of crystals, the solution is drawn off and the tube carefully dried. It is then evacuated, and the water is driven off by heating. At first the heating is gentle, but finally the tube is fired at the maximum temperature the glass will stand. This gives the tube a smooth sodium resistant inner surface.

The potassium-sodium alloys, lying within the composition range 45 to 90 per cent potassium, are liquid at room temperature.

Alkali-earth metals. The chief uses of the alkali-earth metals, as getters, depend on their reactions with oxygen to form oxides, with carbon dioxide to form carbides and oxides, with water to form hydrides and oxides, and with nitrogen to form nitrides.

When fresh calcium filings are heated in a quartz tube or heavy-walled Pyrex side tube, connected to an apparatus such as a thermopile, the calcium reacts with all the residual gases (except the noble gases). A fairly good vacuum can be obtained with such a side tube even when starting at atmospheric pressure. For example, the argon spectrum may be obtained in a discharge tube evacuated from atmospheric pressure once or twice with such a calcium side tube. Each time the tube is evacuated from atmospheric pressure with calcium, the residual pressure of argon (calculated from its abundance in the atmosphere) is increased by an amount 7×10^{-2} mm.

Barium is a more reactive metal than calcium.[4] It is used as a getter for commercial radio tubes. For this application, the metal is sometimes cast in a seamless tube of nickel or copper which is drawn down to wire. These composite wires are known as Niba and Cuba wires. The wires are cut into short lengths, which are introduced into radio tubes and other places where the getter action is desired. The volatile

[4] Barium and strontium metal of a guaranteed purity of 99.5 per cent may be purchased from the Varlacoid Chemical Company, 15 Moore Street, New York City.

core metal is subsequently boiled out of the nickel or copper covering tube by means of heat generated with a high-frequency induction coil.

Mercury. Although mercury approaches the noble metals in chemical inertness, it is easily contaminated, especially by other metals. This is because, as a liquid, it is a fairly good solvent. A simple test for the purity of a sample of mercury

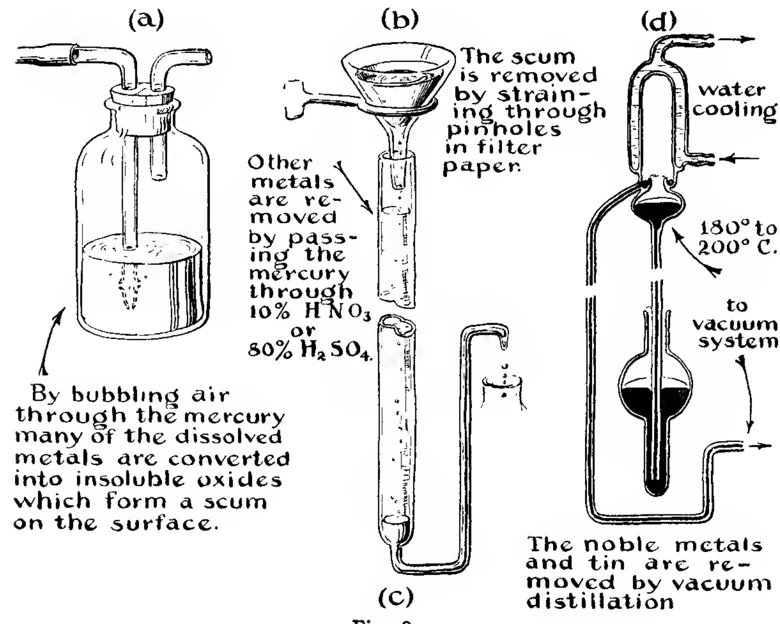

Fig. 9.

is to raise a clean glass rod slowly up through the metal surface. If the mercury is clean, the glass will come up without any adhering mercury droplets.

The contaminations commonly found in mercury may be classified according to the manner in which they can be easily removed. First come surface contaminations by materials which do not dissolve in the liquid metal and may, accordingly, be removed by filtering the metal through pinholes in filter paper or through a chamois skin. Second, there are the dissolved metals. Those which are oxidizable are first con-

verted to insoluble oxides by the blowing of air through the mercury as shown in Fig. 9(a). The oxides form a scum on the mercury surface and may later be filtered off. Mercury is practically free of impurities of this type if, after air has been blown through the liquid metal $\frac{1}{2}$ hour, no scum has formed on the surface. The alkali metals fall into this class of impurities; here also belong zinc, with a high vapor pressure, and copper and lead, with low vapor pressures. These metals, which are more reactive than mercury, can also be removed by exposing the mercury to a solution of 10 per cent HNO_3 or 80 per cent H_2SO_4. This is shown in Fig. 9(b). Thirdly, there are the dissolved metals, such as the noble metals and tin, which cannot be removed by oxidation or acid. Copper and lead may also be considered as belonging to this class of contaminations. These metals are removed by vacuum distillation of the mercury at a temperature of about 180° to 200°C. (at which temperature the mercury distills at the rate of approximately $\frac{1}{2}$ g/cm^2/sec.) as indicated by Fig. 9(c).

The vapor pressure of mercury is given in Table I. It is to be noted thoughtfully that at room temperature the

TABLE I

VAPOR PRESSURE OF MERCURY

Temperature (°C.)	Vapor Pressure (mm)
0	.0002
20	.0013
100	.27
200	17

vapor density of mercury is many times greater than the accepted nonpoisonous concentration limit, which is 1 milligram of mercury per cubic meter. According to Stock, continual breathing of air containing only 15 micrograms per cubic meter of mercury for a few weeks will make most

persons ill.[5] The vapor pressure of mercury is hazardously high in many laboratories. In a Berlin physical laboratory the typical concentration of mercury vapor in the air was found to be about 20 to 60 micrograms per cubic meter; in one room it was 500 micrograms per cubic meter. Heat produced by turning on mercury pumps doubled the concentration of mercury vapor in the air.[6]

Platinum metals. Platinum is chemically resistant to alkalies and hydrofluoric acid. However, it is attacked by chlorine vapor and aqua regia. Metallic salts should not be heated in platinum under conditions which may result in the reduction of the metal and the consequent debasement and embrittlement of the platinum. This applies particularly to lead salts. The elements phosphorus and silicon also attack platinum and make it brittle, and they may change its other properties. For example, even the small amount of silicon introduced into the platinum when it is heated in contact with porcelain in a reducing atmosphere makes an appreciable change in the thermoelectric power and electrical resistance.

Platinum is so ductile that wires may be drawn directly as fine as 20μ diameter. By Wollaston's procedure a platinum rod is covered with a close-fitting silver tube, and this composite rod is drawn through wire dies. After the silver has been etched off the final wire with nitric acid, the platinum wire obtained may be as small as $\frac{1}{2}\mu$ in diameter. Wollaston wire is often used for fuses to protect delicate instruments.[7]

A physical property of platinum which is of interest to the physicist is its "transparency" to hydrogen gas at temperatures above 700°C. (See Fig. 10.) This property is employed to obtain very pure hydrogen.

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[5] Stock, A., and Cucuel, F., *Ber. deutsch. chem. Ges.*, *67*, 122 (1934).

[6] Müller, K., and Pringsheim, P., *Naturwiss.*, *18*, 364 (1930). See also Turner, J. A., *Pub. Health Bull.*, *39*, No. 8 (1924). Goodman, Clark, "Mercury Poisoning, A Review of Present Knowledge," *Rev. Sci. Instruments*, *9*, 233 (1938).

[7] Wollaston and Taylor process wires are handled by Baker and Company, 54 Austen Street, Newark, New Jersey.

Littlefuses are obtainable from radio supply houses.

Platinum is a refractory metal. For this reason it may be used for furnace windings and as a base for oxide cathodes.

Iridium is harder and more resistant to chemical attack than platinum; it is not attacked by aqua regia. Accordingly, it is often alloyed with platinum in proportions up to 30 per cent to yield a metal which is superior to platinum in respect to chemical resistance and hardness.

Rhodium is alloyed with platinum (90 Pt to 10 Rh) to yield the LeChatelier thermocouple alloy. Rhodium is a bright inert metal and for this reason it is used for electroplating other metals.

Osmium is the most refractory metal of the platinum family, with a melting temperature of 2700°C. It was once

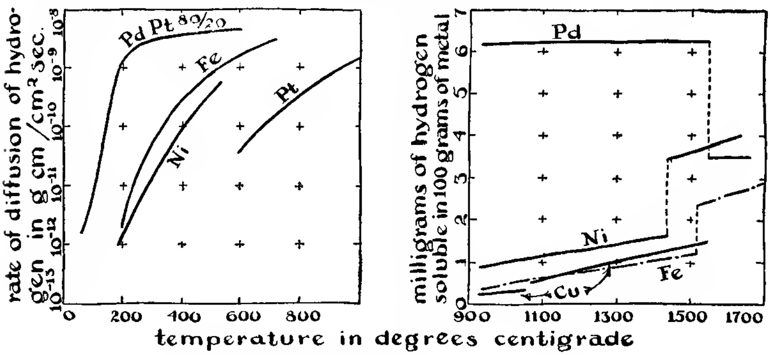

Fig. 10.

Borelius, G., and Lindblom, S., *Ann. d. Physik*, *82*, 201 (1927). Smithells, C. J., and Ransley, C. E., *Roy. Soc., Proc.*, *150*, 172 (1935). Sieverts, A., *Zeits. f. Metallkunde*, *21*, 37 (1929).

used in incandescent lamps but has now been replaced by tungsten for this use. Incidentally, it is the heaviest known substance, having a density of 22.5 g/cm³.

Palladium is the least noble of the platinum metals. It oxidizes when heated in air and is dissolved in nitric acid. Hydrogen diffuses through palladium more rapidly than through platinum. At atmospheric pressure palladium will dissolve about 6 mg H_2 per 100 g of metal to form the "alloy" Pd_2H. The hydrogen is given off again if the metal is heated,

in vacuum, to temperatures above 300°C. (See Fig. 10.) This property affords a convenient source of extremely pure hydrogen in small quantities.

The refractory metals: Tungsten, molybdenum, tantalum, and so forth. Tungsten is the most refractory metal and also the strongest. Wires of .0014 inch in diameter exhibit a tensile strength of 590,000 lbs./square inch. Tungsten is quite "unorthodox" in its behavior with respect to cold working and heat. Passing it through dies makes it more ductile, while heating it to a temperature greater than 1000°C. causes recrystallization and makes it brittle, a situation just opposite to the behavior of most metals. The ductility of tungsten at ordinary temperatures is due to its long fibrous crystal grains. Fig. 11 shows the ductility of tungsten at various temperatures. It will be noted that recrystallized brittle tungsten is ductile if heated to temperatures greater than 200°C.

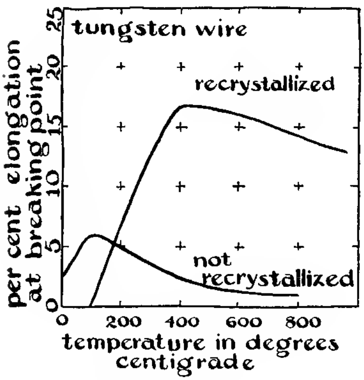

Fig. 11.

Espe, W., and Knoll, M., *Werkstoffkunde der Hochvakuumtechnik*, page 18. Berlin: Julius Springer, 1936.

Traces of water vapor are corrosive on the tungsten filaments in vacuum electric lamps. The water molecule reacts with hot tungsten to form tungsten oxide and atomic hydrogen, both of which evaporate to the glass wall of the bulb, where, owing to catalytic effect of the glass, they react to give metallic tungsten and water vapor again. The water molecule is now free again to repeat its action on the tungsten filament.

Tungsten reacts with oxygen and carbon monoxide, in vacuum, to form oxides and carbides. Tungsten is not attacked or affected by mercury vapor or hydrogen gas. In air, at a yellow heat, tungsten reacts with oxygen to form volatile oxides, which distill off as white smoke.

Molybdenum is more ductile than tungsten. Otherwise, it is very similar to tungsten, and the two metals form alloys in all proportions. Some of these alloys are used commercially. Their properties are, in general, a compromise between the higher melting temperature of tungsten, on the one hand, and the greater workability and machinability of molybdenum, on the other.

Molybdenum and tungsten do not soft-solder or amalgamate with mercury, but both metals may be welded to nickel or Advance alloy. Nickel is frequently welded to tungsten to facilitate connecting it by spot-welding, soldering, or brazing to other less refractory metals.

Tungsten or molybdenum may be cleaned by heating the metal to a red heat and rubbing its surface with a piece of potassium or sodium nitrite.

In many respects tantalum is like molybdenum and tungsten.[8] Tantalum, when it is very pure, is one of the most ductile metals. However, when heated in hydrogen or air, tantalum becomes brittle. To anneal tantalum, it must be heated to about 800°C. in a vacuum better than 5×10^{-2} mm of mercury. Because tantalum readily gives off occluded gas if heated above 800°C., it is used as a construction material in vacuum tubes.

To spot-weld this metal successfully, it must be submerged under carbon tetrachloride or water. It may be machined using carbon tetrachloride as a cutting fluid, and spun using hard laundry soap as lubricant.

Columbium occurs with tantalum and has many properties in common with it. It is less refractory and more ductile than tantalum. It is used as a substitute for tantalum.

Rhenium is the heaviest member of the manganese subgroup in the periodic table, and it is very refractory, its melting temperature being only about 200° below that of tungsten.

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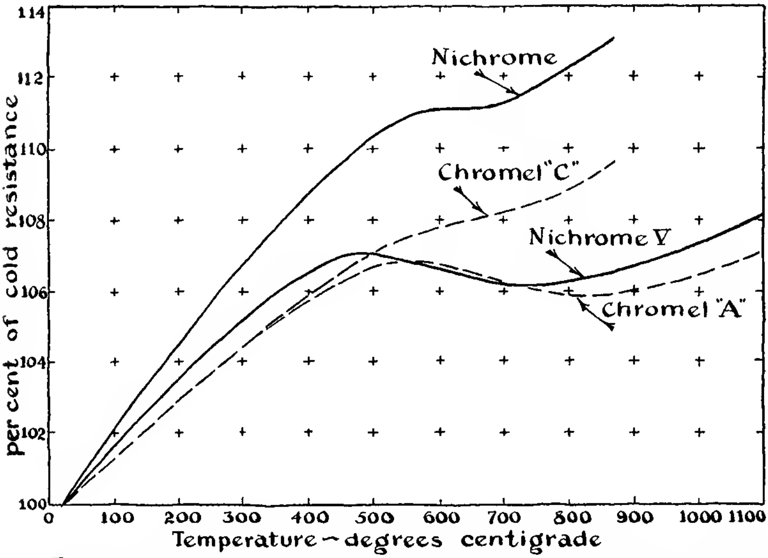
[8] Tungsten, molybdenum, and tantalum may be obtained from the Fansteel Products Company, Inc., North Chicago, Illinois, and Callite Products Company, 595 Forty-Ninth Street, Union City, New Jersey.

Alloys. *Invar.* The iron-nickel alloy, 63.5 Fe, 36 Ni, 0.5 Mn, is known as Invar. Its coefficient of expansion is only low for temperatures below 120°C., being 4×10^{-7} per degree centigrade. The heat conduction of Invar is also very low, being only $\frac{1}{40}$ that of copper. Invar does not corrode. It is used for the construction of surveyor's tapes and instruments in which the dimensions are required to remain constant in spite of temperature changes. The alloy melts at 1425°C.

Electrical-resistance alloys.[9] Nickel-chromium alloys are characterized by a high electrical resistance (about 58 times that of copper), a low temperature coefficient of resistance, and a high resistance to oxidation. Examples are Chromel



These curves represent average values. Actual samples of the materials may depart from these values from negligible amounts at 20°C to as much as ±4½% at 1100°. For precise work samples of the material to be used should be tested.

Fig. 12.

[9] Chromel is manufactured by the Hoskins Manufacturing Company, Detroit, Michigan. Nichrome is manufactured by the Driver Harris Company, Harrison, New Jersey.

A and Nichrome V, of which the typical composition is 80 Ni and 20 Cr, with the melting point at 1420°C.

When some iron is added to the nickel-chromium alloys, it makes them more ductile. Nichrome and Chromel C are examples of these iron-containing alloys. The typical composition of Nichrome is 60 Ni, 12 Cr, 26 Fe, 2 Mn, and of Chromel C, 64 Ni, 11 Cr, 25 Fe. The melting temperatures of these alloys are 1350° and 1390°C. respectively. The change of resistance with temperature for these alloys is illustrated in Fig. 12.

Thermocouple alloys. Chromel P gives a useful base-metal thermocouple in combination with the alloy Alumel (94 Ni, $2\frac{1}{2}$ Mn, $\frac{1}{2}$ Fe). The thermocouple wires are welded together under a borax flux to make the junction. None of the Chromels braze, but they all may be welded to nickel.

Constantan (45 Ni, 55 Cu) has practically zero temperature coefficient of resistance up to a temperature of 400°C. Also, it gives a high thermal e.m.f. against copper, making an excellent thermocouple. Constantan exhibits high resistance to oxidation and corrosion. It solders easily.

Solders. Solders are required to flow onto the surface of the metals to be joined and to alloy with the surface layers of the metals. Also, they should be ductile, have high strength, and be noncorrosive.

Silver solder best meets all these requirements. It is used for joining brass, steel, stainless steels, and many other metals. Silver solders are, in effect, brazing alloys of the composition (4 Cu to 3 Zn) with silver added. A solder melting at 693°C. contains 65 per cent silver, while one melting at 760°C. contains but 20 per cent silver.

High-quality soft solder is half tin and half lead. Solders are often made with a higher content of lead, since the tin component is more expensive than lead. Such solders are inferior, since it is the tin component that makes the solder run well and adhere well. "Half-and-half" solder melts at 188°C. The properties of various solders are given in Table II.

TABLE II

PROPERTIES OF SOLDERS

Solder	Composition	Melting Point (°C.)	Flux
Soft solder:			
Wood's metal	Bi 50, Cd 12.5, Pb 25, Sn 12.5	61	*A*
soft solder eutectic	Pb 36, Sn 64	181	*A*
half-and-half	Pb 50, Sn 50	188	*A*
Hard solder:			
silver solder	Ag 45, Cu 30, Zn 25	720	*B C*
brazing compound	Cu 54, Zn 46	875	*B*
Intermediate solder	Ag 20, Cu 3, Zn 2, Sn 75	400	*A*

Composition of fluxes:
A—(a) Flux: 40 $ZnCl_2$, 20 NH_4Cl, 40 H_2O.
(b) Paste: 90 Petrolatum, 10 NH_4Cl.
(c) Solution of rosin in alcohol.
B—(a) Thin paste composed of water and 10 parts powdered borax and 1 part boracic acid.
(b) Borax applied dry.
C—Handy flux. Manufactured by the Handy and Harman Company, Bridgeport, Connecticut. This is an excellent flux. It has a lower melting point than borax.

Brass and bronze. Brass is the most widely used construction material in the physical laboratory. It is fundamentally a copper-zinc alloy. Red brass (10 to 20 per cent zinc), or so-called Tombak alloy, is used for making flexible corrugated tubes (such as Silphon tubes) when maximum ductility is required; yellow or common brass, which contains copper and zinc in the proportions 65 to 35, with small lead additions to increase its machinability, is used where springiness is desired.

Brasses are less expensive than the copper-tin alloys or bronzes. They are also softer and more ductile. Brasses are used for drawing and rolling, whereas bronzes are primarily casting materials. Bronze castings are much more likely to be vacuum tight than brass castings. Also, because bronzes have small crystals of the hard brittle compound Cu_4Sn, they make good bearing metals (the 68.2 copper

bronze, Cu_4Sn, is the true speculum metal used for optical gratings and for mirrors).[10]

Duraluminum. The aluminum alloy with composition 95 Al, 4 Cu, $\frac{1}{2}$ Mg, $\frac{1}{2}$ Mn, is known as Duraluminum. Duraluminum is employed extensively in many cases where brass was formerly used. For about 45 minutes after it has been heat treated at 530°C. and quenched in water, Duraluminum is ductile and can be rolled, bent, or cold-worked. After this interval a copper aluminum compound is precipitated out of solid solution, and this precipitate "keys" the crystals of the alloy at their slip planes, giving the alloy increased hardness and strength. The tensile strength, originally 30,000 lbs./square inch after quenching, becomes as great as 75,000 lbs./square inch after cold-working and aging. Duraluminum rivets are frequently stored in buckets cooled with dry ice. They may be used as desired, for this low temperature arrests the aging process, and the metal does not harden until after it has warmed up to room temperature.

Wood.[11] Two kinds of wood are obtained from a tree: heartwood and sapwood. The heartwood is formed early in the life of the tree and, as the name implies, is found near the center of the trunk. Protoplasms present when the tree is young are gradually replaced by deposits of gum, minerals, tannin, and pigments to form this heartwood as the tree becomes older. These substances make it heavier, stronger, and in most cases darker than the sapwood. The heartwood of the redwood tree, which is particularly free from gums and oils, is an exception. In other heartwoods there are abun-

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[10] Lord Ross' famous 60-inch mirror contains 70 Cu 30 Sn; an old Roman mirror contains 64 Cu, 19 Sn, 17 Pb; an Egyptian mirror contains 85 Cu, 14 Sn, 1 Fe. Brady, G. S., *Materials Handbook.* New York: McGraw-Hill Book Company, 1931.

[11] Fowle, F. E., *Smithsonian Physical Tables.* Washington: The Smithsonian Institution, 1934.

Koehler, Arthur, *Properties and Uses of Woods.* New York: McGraw-Hill Book Company, 1924.

Marks, L. S., *Mechanical Engineers' Handbook.* New York: McGraw-Hill Book Company, 1930.

"Mechanical Properties of Woods Grown in the United States," Department of Agriculture, Bull. 556.

dant deposits. For example, in lignum vitae, these compounds produce an oiliness (especially when the wood is wet) which makes it suitable as a bearing material.

Sapwood, or the outer part of the tree, is more pliable than heartwood. Therefore, in using such woods as hickory and ash, which are noted for their adequate strength, the outer part of the trunk may be preferred to the heartwood because of its pliability.

Effects of temperature. Some of the effects of temperature on wood are due to the gum deposits. High temperature softens these gums, making the wood weaker and more liable to split. On the other hand, low temperatures produce increased brittleness.

The thermal expansion of wood in directions parallel and perpendicular to the grain is given in Table III. It will be noted that the expansion parallel to the grain is less for wood than for most of the metals. This property is a useful one, and it should be kept in mind and used in the construction of instruments where invariance of length is desired, as, for example, in a telescope tube, in which the relative distance between the optical components should not change with changes in temperature.

TABLE III

Linear Expansion of Wood and Various Other Solids per Unit Length per Degree Centigrade $\times 10^{-6}$

Material	Expansion	
Aluminum	23.0	
Cast brass	18.7	
Cast iron	12.0	
Steel	11.4	
Glass, plate and crown	9.0	
	Parallel	Perpendicular
Maple	6.3	48
Oak	4.9	55
Pine	5.4	34
Walnut	6.5	48
Sugar maple	2.1	..

The heat conductivity of several common types of wood is given in Table IV. The conduction of heat is from two to four times as great along the grain as it is across it. The conductivity depends, in a large measure, on the moisture content. To obtain maximum heat insulation, the wood must be dry. To keep it dry, particularly if the wood is to be exposed to low temperatures, it should be coated with paraffin.

TABLE IV

HEAT CONDUCTION OF WOOD AND SOME OTHER MATERIALS IN C. G. S. UNITS

Material	Specific Gravity	Heat Conductivity
Wood:		
Balsa	0.12	.00012
Hard maple	0.61	.00038
White pine:		
along the fiber	0.50	.00027
across the fiber	0.50	.00010
Cotton—firmly packed	....	.00010
Hair, felt	....	.000085

Effects of moisture. One drawback to the use of wood as a material for construction, especially for scientific apparatus, lies in the fact that its dimensions may change considerably with its change in moisture content. We may take the shrinkage from the green to the dry condition as an index of the changes one may expect with changes in humidity and residual curing. This shrinkage (radial and tangential) for several woods is given in Table V.

TABLE V

SHRINKAGE OF WOOD FROM THE GREEN TO THE DRY CONDITION

Wood	Tangential (%)	Radial (%)	Ratio
Magnolia, evergreen	6.6	5.4	1.2
Redwood	4.4	2.6	1.7
Sugar maple	9.5	4.9	1.9
Sugar pine	5.6	2.9	1.9
Pine, northern white	6	2.3	2.5
Range of all commercial woods	4.2 to 14	2 to 8.5	..

Wood Handbook, United States Department of Agriculture, September, 1935.

Among the hardwoods, evergreen magnolia is prized as one which does not warp. This may be understood by referring to Table V, where we see that of all the woods it is the one whose radial and tangential shrinkages are most nearly equal.

Most of the shrinkage in wood is at right angles to the grain; the longitudinal shrinkage, taken from the green to the cured condition, is seldom greater than $\frac{1}{10}$ to $\frac{1}{3}$ per cent. (It is greater than this for some woods, particularly woods grown under strong compression. Yellow pine compression wood, for example, may shrink longitudinally as much as $2\frac{1}{2}$ per cent when it is cured. Redwoods also exhibit considerable longitudinal shrinkage. However, longitudinal shrinkage is negligible for most of the other woods.) This property of wood, in addition to the low thermal expansion parallel to the grain, explains why wood has been used so successfully for rulers; it may suggest other applications for wood in the laboratory.

When a piece of wood is carved or cut to precise dimensions that are to be maintained, it should be painted at once with several coats of shellac, in order to maintain the moisture equilibrium already established. Linseed oil is less effective, while paraffin is more effective than shellac for this purpose. Molten paraffin is applied by pouring it over the surface with a spoon. The boiling of wood in paraffin causes it to become brittle.

Strength of wood. Strength and rigidity do not vary from wood to wood as much as is commonly supposed. For example, the bending strength of shagbark hickory is only 2.6 times as great as that of sugar pine, and pine is inferior to hickory in rigidity by a factor of only 1.9. Pine differs from hickory not so much in stiffness as in brittleness—pine breaks where hickory bends. Spruce, of all the common woods, has the highest strength for its weight.

The tensile strength of wood varies in different directions. Along the grain its strength is ordinarily from ten to twenty times as great as it is across the grain. Also, the modulus of

TABLE VI

PROPERTIES OF WOOD

Property	Sugar Pine	Persimmon	Sugar Maple	Evergreen Magnolia	Shagbark Hickory
Specific gravity	.37	.81	.62	.51	.74
Static bending: fiber stress at elastic limit (1000 lbs. per sq. inch)	6.4	15.4	10.4	7.8	11.9
Static bending: modulus of rupture (1000 lbs. per sq. inch)	8.6	23.7	15.8	12.5	22.6
Static bending: modulus of elasticity (1,000,000 lbs. per sq. inch)	1.21	2.48	1.82	1.48	2.29
Static bending: work in bending to maximum load (lbs. per cu. inch)	5.0	16.9	13.6	12.3	26.3
Impact bending: energy of dropped hammer to cause complete failure (relative)	26	54	51	38	100
Compressional fiber stress at the elastic limit parallel to the grain (1000 lbs. per sq. inch)	4.74	9.21	6.06	3.94	...
Maximum crushing strength (1000 lbs. per sq. inch)	5.2	14.1	8.6	6.6	10.7
Compressional fiber stress at the elastic limit (perpendicular to the grain) (1000 lbs. per sq. inch)	.64	3.91	1.62	1.25	2.47
Tensional strength perpendicular to the grain (1000 lbs. per sq. inch)	.35	1.52	.77	.78	...
Shearing strength parallel to the grain (1000 lbs. per sq. inch)	1.1	2.7	2.5	1.7	2.3
Hardness on the side (relative)	4	100	45	35	...

elasticity is correspondingly greater along the grain. This anisotropy is avoided in plywoods, formed by gluing together three, five, seven, or nine layers of wood, the consecutive layers being arranged with their grain axes lying mutually perpendicular. Plywoods with the greatest number of layers are most resistant to splitting and are most nearly isotropic. The thick plywoods use cores of wormy chestnut. The ease with which woods are cut and carved is proportional

to their homogeneity or the degree of similarity between the physical properties of the spring and the summer growth. Also, it is desirable to have a fine grain, a quality possessed by many hardwoods, especially mahogany. Of the common softwoods, poplar and sugar pine are the most homogeneous and easiest to work.

Some wood substitutes are now available which are nearly isotropic. These are formed of bonded cellulose fibers. Although they are quite homogeneous, they are not so easily worked as wood with the plane and chisel, and nailing splits them. They can be sawed with the ordinary wood saw. Masonite is an example of such a wood substitute.[12] It comes, chiefly, in three grades, a light material which is a good heat insulator, a harder material which is suitable for making boxes for instruments, and an oil-tempered waterproof material.

Waxes and cements. The physicist uses waxes and cements to seal windows into apparatus, tubes in plates, tubes together, and so forth. He uses them also to support and fasten down lenses, prisms, and mirrors. Of all waxes available, the most useful for making improvised supports and seals is the so-called universal wax.

Universal wax. Universal wax is made from 1 part Venetian turpentine and 5 parts beeswax. It is usually, although not necessarily, colored with vermilion. It should be made up in small quantities, for it oxidizes, with the result that it becomes hard and loses its desirable properties. Old pieces may be useful if the outside oxidized layers are removed and discarded. The usefulness of this wax depends upon its adhesive and plastic properties. It is quite plastic at the slightly elevated temperature attained when the wax is worked between the fingers. When it cools, it becomes fairly rigid.

Beeswax and rosin. Beeswax and rosin compound is prepared by melting together equal parts of beeswax and rosin. Its softening point is at the temperature which just begins to

[12] Masonite Corporation, 111 West Washington Street, Chicago, Illinois.

feel hot (47°C.) and it is liquid at 10° above this temperature. Its outstanding property is its adhesiveness to cold metal. It is not very strong, but its strength is adequate for sealing vacuum systems and for fixing apparatus, as, for example, fastening a prism to the prism table of a spectrometer. It can be applied with a brush, an eye-dropper, or the blade of a knife. To secure the best bond to cold metal, the wax should be applied smoking hot with an eye-dropper or a knife. When it has been used for sealing down a bell jar, it can be removed with a putty knife, remelted, and used over and over. The smoking temperature distills off some of the beeswax, causing the compound to become harder. It may be retempered by adding more beeswax. There are many applications for which this wax is not suitable because it shrinks a great deal on solidifying. It is best "dissolved" by a mixture of equal parts of carbon tetrachloride and ethyl alcohol.

Shellac. In its pure state, shellac in stick form is known as lapidarist's cement. It has a high tensile strength and shear strength. (Both are about 3800 lbs./square inch.) Only the natural orange shellac possesses this high strength. The main ingredient of the better grades of sealing wax and especially banker's wax is shellac.

Shellac is used in commerce chiefly for the manufacture of phonograph records, varnishes, and as an insulator in the electrical industry. It has a higher resilience than almost any other wax, and it is this property which gives long life to phonograph records.

The best solvent for shellac is alcohol. This solution yields a varnish which has many uses in the laboratory. When it is very thick, it is useful for hunting leaks in vacuum systems.

Shellac is polymerized by heat, giving a product which is harder, has a higher softening temperature, and is less soluble in alcohol than the uncured material. This polymerization is accompanied by a chemical loss of water and a two- to threefold increase in molecular weight. Half of the uncured

shellac is transformed into this harder variety by heating for 30 hours at 90°C.; at 150°C. it is completely transformed in 3 hours. When the pure shellac is to be used as a cement, it is desirable to have it in the unpolymerized state.

Commercial shellac may legally be designated as pure although it may contain as much as 3 per cent rosin. This materially weakens it. It is possible, however, to obtain shellac which is free from this adulterant.[13]

Tempered shellac. When shellac is tempered with 20 to 40 per cent wood tar, we have a wax similar to the familiar DeKhotinsky cement. This wax is not affected by water, carbon disulphide, benzol, petroleum benzine, or turpentine. It is affected only slightly by ether, chloroform, and sulphuric, nitric, or hydrochloric acids.

When DeKhotinsky cement is heated in a flame, it emits an odor and is somewhat inflammable. A new variety of tempered shellac, which has no odor and is not so inflammable, is now sold by the Central Scientific Company under the trade name of Sealstix. Sealstix has a greater working range of temperature than pure shellac and a very high strength.

Shellac can be tempered with butyl phthalate. The resulting compound has a very low vapor pressure and is particularly suitable for high-vacuum work. It is odorless and relatively noninflammable.

Shellac can also be tempered to varying degrees with oil of cassia. About 10 per cent oil is quickly added to the molten shellac. The oil gives a compound with an agreeable odor. It is useful for many purposes when its vapor pressure is not important.

Shellac can also be tempered with amyl acetate for use when the vapor pressure of this constituent is unobjectionable. Most of this solvent evaporates when the cemented elements are maintained at an elevated temperature (80°C.) for an hour or so. A mixture of 2 ounces of amyl acetate to

[13] Pure orange shellac is obtainable from William Zinsser and Company, 516 West 49th Street, New York City.

100 g of shellac gives a cement with a strength in excess of 2500 lbs./square inch.[14]

Picein. This sealing compound is characterized by low vapor pressure, plasticity at room temperature, and chemical inertness. Its low working temperature (it becomes quite plastic at 50°C. and is liquid at 80°C.), together with its adhesiveness, recommends it for many applications. Besides its use for sealing tubes together and repairing leaks in vacuum systems, it is also used in the optical industry. It is practically unaffected by alcohol. Picein is immune even to a short immersion in cold dichromate cleaning solution. It is dissolved by benzol and turpentine. Its insulating qualities are said to be as good as amber if it is not overheated. It comes in two grades, the second being characterized by a liquefying temperature of 105°C.[15]

Apiezon compounds.[16] Apiezon compounds are especially refined residues of paraffin oils freed from high vapor pressure constituents.

The sealing compound "Q" contains graphite. It is plastic at ordinary temperatures and has a vapor pressure of 10^{-4} mm at room temperature, and, applied to ordinary twine, it is recommended as a packing for vacuum valves.

Apiezon wax "W" has the lowest vapor pressure of any of the waxes now available. It is necessary to heat this wax to 180°C. in order to raise its vapor pressure to 10^{-3} mm of mercury. It melts at 70°C., but it can best be applied at 100°C. or higher. Molten, it wets metals and glass and is quite fluid. It is fairly strong at ordinary temperatures. It is soluble in zylene.

Silver chloride. Silver chloride is recommended for seals that must hold at elevated temperatures. It melts at 455°C. It is insoluble in water, alcohol, benzol, and acid. It is,

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[14] This cement was developed by Marcus H. Brown.

[15] Picein and a rubber packing material, *Dichtungsgummie*, are obtainable from the distributing agents of the New York Hamburg Rubber Company, Schrader and Ehlers, 239 Fourth Avenue, New York City.

[16] Apiezon compounds are obtainable from the James G. Biddle Company, Philadelphia, Pennsylvania.

however, soluble in a solution of sodium thiosulphate. Most metals and glasses are wet by fused silver chloride. It is useful for sealing optically worked windows on a discharge tube. The window, after being sealed, is cooled slowly to prevent it from cracking.

Espe and Knoll describe an enamel which they recommend for cementing optical plane parallels on a discharge tube.[17] This is a mixture of clay and boracic acid, the melting point of which is 450° to 600°C. It is applied, as is silver chloride, by heating both the window and discharge tube in an electric oven.

The bonding materials which we have considered above are thermoplastics. With the exception of shellac, the changes in their properties are reversible with temperature. We will now treat those substances which set, which can be vulcanized, and which polymerize by the application of heat. They include the synthetic resins, rubber cements, and inorganic cements.

Synthetic resins treated of here fall into three broad divisions. These are, first, the polymerized phenol aldehydes, of which Bakelite is an example; second, the condensation products formed by polyhydric alcohols with polybasic acids (these are termed alkyd resins, of which Glyptal is an example); and third, the polymerized derivatives of methacrylic acid, of which Lucite and Plexiglas are examples.

Bakelite.[18] Bakelite comes in several forms that are useful to the physicist. The properties of these vary from liquid or soluble solids in the uncured condition to stable insoluble solids in the cured condition. Bakelite in the latter condition is obtainable in the form of clear, transparent sheets, blocks, tubes, and so forth. This material is light (density, 1.27) and strong (7000 lbs./square inch), is a good electrical insulator, and is insensitive to moderate heat. In this completely polymerized form it does not melt, and it chars only

[17] Espe, W., and Knoll, M., *Werkstoffkunde der Hochvakuumtechnik,* page 157. Berlin: Julius Springer, 1936.

[18] Bakelite is manufactured by the Bakelite Corporation of America, 247 Park Avenue, New York City.

at a temperature of 285°C. Chemically, it is relatively inert. The completely polymerized Bakelite is unaffected by hot water, oils, greases, alcohol, acetone, benzene, dilute mineral acids, including hydrofluoric, and soap. It is practically nonhygroscopic. These properties recommend it as a material for making transparent chemical apparatus, such as burettes, pipettes, beakers, and so forth. Transparent forms of Bakelite are suitable for making models for photoelastic studies with polarized light.

Several molded and laminated products bonded with Bakelite are available commercially. These have canvas, wood fiber, asbestos, or graphite as a base. The asbestos-base material is especially heat resistant, and the graphite-base material is useful for dry bearings.

Bakelite varnishes usually consist of solutions of the unpolymerized form. After application and drying, the varnish films are transformed to the insoluble form by baking.

Bakelite cements come in the form of solids and viscous liquids. The solid form melts at about 80°C. (in hot water) and is transformed by heat to a form which does not melt. The liquid forms contain a volatile solvent. It is first necessary to evaporate this by preliminary heating of 1 to 4 hours at 80°C., after which the residue is polymerized by heating for 2 hours at 120°C. A self-hardening cement is available which will set at room temperature. Vacuum seals made with these cements have a low vapor pressure and can be used to temperatures slightly above 100°C.

A general-utility cement can be made by mixing Bakelite varnish with red lead. This hardens rapidly and will withstand high pressure, steam, oil, and moderate heating.

Alkyd resins.[19] Alkyd resins are formed by the condensation of phthalic anhydride on glycol, glycerol, or other polyhydric alcohols. Glycol phthalate is useful as a vacuum-sealing cement because of its low vapor pressure, fluidity, and wetting power when melted. In addition, it

[19] Alkyd resins may be obtained from the General Electric Company.

may be cured to give it increased strength and inertness. It is also noted for its adhesiveness to aluminum. It is inert toward mineral oils. Dehydrating catalysts, such as zinc oxide, hasten the cure of these compounds and serve as a filler to economize on the resin, as, for example, in lamp-basing cements.

Lucite and Plexiglas. Lucite and Plexiglas are trade names for methyl (and ethyl) methacrylate, polymerized derivatives of methacrylic acid.[20] These materials are sold as a cast resin in the form of sheets, rods, and tubes, as a thermoplastic powder, and as the unpolymerized liquid.

The methyl methacrylate monomer is a mobile liquid which can be polymerized in almost any desired form. The monomer boils at 100°C. and has a heat of polymerization of about 80 calories/g. As it is obtained from the factory, it contains an inhibitor, such as hydroquinone or pyrogallol, to prevent it from polymerizing at room temperature. To use the liquid, this inhibitor is removed by washing with caustic, the liquid is dried, and an accelerator, usually benzoyl peroxide, is added to catalyze the polymerization. The volume of the monomer is 20 per cent greater than the volume of the polymer finally obtained, so that considerable art must be invoked to prevent the formation of voids when the monomer condenses.

The polymerized methyl methacrylate, Lucite, has the optical properties given in Table VII. (See also Table VI, Chapter IX.) The polymers are inert toward water and insoluble in the straight chain hydrocarbons, alcohols, and ethers and in most fats, oils, and waxes. They are, however, dissolved by lower ketone and ester solvents, and by mixtures of the aromatic hydrocarbons when small amounts of alcohol are added.

These polymers are vastly different from Bakelite and the plastic, Catalin, in respect to cutting. Whereas Catalin and

[20] Lucite is manufactured by E. I. duPont de Nemours and Company, Wilmington, Delaware. Plexiglas is manufactured by Röhm and Haas Company, 222 West Washington Square, Philadelphia, Pennsylvania.

TABLE VII

PERCENTAGE OF ULTRAVIOLET TRANSMISSION OF LUCITE AT DIFFERENT WAVE LENGTHS

Wave Length (Å)		Transmission (%)
Sheet Thickness 1 inch	Sheet Thickness 0.1 inch	
3020	....	1
3120	2860	5
3140	2920	12
3170	2980	25
3280	3020	50
3500	3340	75

Bakelite quickly remove the edge from high-speed steel (in fact, cold-rolled steel is just about as good for cutting them as high-speed steel), Lucite and Plexiglas can be cut by the hour without the edge of the tool becoming dulled.

Fish-glue cement. A cement which is inert toward most organic solvents is made from a thick solution of 3 ounces of fish glue, $\frac{1}{4}$ ounce of potassium bichromate, and a little ammonia. The cement so formed is allowed to dry and is then heated in an air oven until it assumes a chocolate-brown color. This cement is often used on Pulfrich refractometers.

Rubber cements. Rubber cements are conveniently classified as follows: nonvulcanizing cements, which attain their strength simply by the evaporation of a solvent; vulcanizing cements, in which a chemical change occurs after the evaporation of the solvent; and thermoplastic cements. Some of the vulcanizing cements contain sulphur, while others are vulcanized simply by painting a vulcanizing liquid, sulphur chloride, on the rubber after it has been applied.

The synthetic thermoplastic rubber-like products Neoprene (manufactured by DuPont Company) and Koroseal (manufactured by the Goodrich Rubber Company) have many useful properties. These materials are remarkably

stable chemically; they are inert toward acids and alkalies, as well as many fats and oils.

Plaster of Paris. This is frequently used to support large glass bulbs containing mercury. The plaster suspended in water to the consistency of a paste is cast between the bulb and a loose-fitting wooden support. Salt shortens the time required for plaster of Paris to set, while a trace of glue acts in the opposite way. The glass may first be wiped with oil so that the plaster will not adhere to it. This facilitates subsequent dismantling.

Litharge and glycerin. This combination gives a cement useful for the same type of applications for which plaster of Paris is useful. It is inert toward water, most acids, and all alkalies, and holds up to temperatures of 260°C. It is prepared by mixing pulverized Litharge (which has been first thoroughly heated at 400°C.) with pure glycerin to the consistency of a paste.[21]

Other irreversible cements. Water glass forms cements when mixed with the carbonates or oxides of calcium, magnesium, zinc, lead, or iron. In a few hours these mixtures set to rock hardness. Combined with talc, water glass makes a cement which holds even at a red heat. This cement will not chip off from glass at liquid air temperatures.

Zinc oxychloride cement is used extensively in dentistry. It is formed from a 60 per cent zinc chloride solution and zinc oxide powder mixed to the consistency of a thick paste. These constituents react to give zinc oxychloride. To insure that the oxide is free from carbonate, it should first be heated until it turns yellow to calcine the carbonates.

Nine parts kaolin mixed with one part borax give a cement useful to 1600°C. The constituent powders are mixed, and water is added to facilitate application. After the water evaporates, the cement is slowly heated to a yellow heat in order to set it.

Insa-lute cement, a commercial product, is a thick white

[21] von Angerer, Ernst, *Technische Kunstgriffe bei physikalischen Untersuchungen.* Friedr. Vieweg und Sohn, 1936.

suspension of refractory substance in water glass. It sets on drying to form a white material having the texture of porcelain. It is an electrical insulator and stands firing to about 1100°F. It adheres to metal, glass, and porcelain. It attacks chromium-alloy wire at elevated temperatures and should not be used in contact with it. One should use a refractory cement such as Alundum cement in contact with chromium-alloy wires.

Glue. Unquestionably, the best bonding material for wood is glue. Glues are more effective for the lighter woods, which contain less oils and resins, than for the dense woods. There are three kinds of glue: casein, blood albumin, and animal glues. The first two are useful for general construction work. The animal glues exhibit greater strength, but they are softened by moisture. Casein glue is made from milk protein and lime. Blood glues contain caustic soda and water glass. Both the latter glues require heat and pressure for their application. They are water resistant and are used for making plywood.

Animal glue is best applied hot. Cabinet and pattern makers usually keep a hot glue pot. For occasional use, however, air-drying glues are quite satisfactory for joining wood as well as leather. Air-drying glue is applied to the surfaces which are to be fastened together. The glue films on these surfaces are allowed to dry until the glue is definitely stringy. At this stage the surfaces are clamped together, and the glue is allowed to become completely dry.

Lubrication. There are two kinds of lubrication with liquids. In the first and most common kind, called complete lubrication, the bearing surfaces are separated by an oil film about .005 inch in thickness. The friction, and consequently the amount of heat produced in the lubricant, depend on the film thickness and viscosity of the liquid.

In the second kind of lubrication the surfaces are in contact. Friction and galling are diminished and prevented by a surface film. The tenacity with which this liquid film adheres and the effectiveness with which it reduces friction

are determined by a quality called the oiliness of the liquid. The lubrication of surfaces in contact is called boundary lubrication. In general, mineral oils are more suitable for the first type of lubrication, and vegetable and animal fats, as well as soaps, are more suitable for the boundary lubrication. The friction in the case of boundary lubrication is usually less when the surfaces are covered with a surface film of high molecular weight. High viscosity (which is associated with high molecular weight) gives more friction in the case of complete lubrication.

Sir Wm. B. Hardy and Miss Ida Doubleday[22] have studied the coefficient of boundary friction for various materials, and the results of their study are illustrated by Fig. 13.

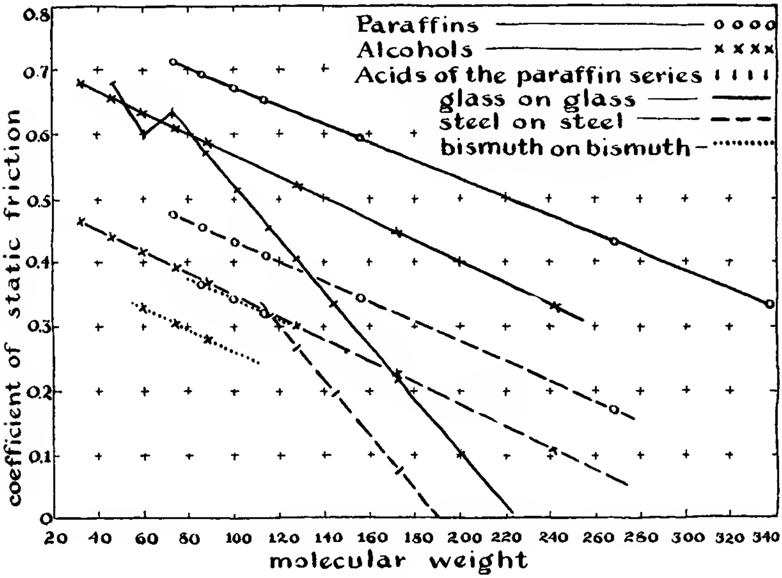

Fig. 13.

The boundary friction is represented in this figure for glass rubbing on glass, steel on steel, and bismuth on bismuth. The coefficient of friction is plotted as ordinate

[22] Hardy, W. B., and Doubleday, Ida, *Roy. Soc., Proc., 100A*, 550 (1921–1922).

against the molecular weight of the lubricant as abscissa. The paraffins and the alcohols and acids of the paraffin series are the liquids used as lubricants.

We see that for very high molecular weights, particularly in the case of the fatty acids, the coefficient of friction is expected to be zero, and, indeed, for some compounds Hardy found the static friction to be less than the minimum amount that he could measure.

Of these results, Hardy and Doubleday say:

It will be seen that for each chemical series, and for each solid, the curve is a straight line. The equation is therefore

$$\mu = b - aM$$

where M is molecular weight and a and b are parameters. The effect of the nature of the solid face is unexpectedly simple. In changing from glass to steel the curve for a series is merely moved parallel to itself, and in changing from steel to bismuth there is a further shifting. Therefore, in the equation the parameter a is independent of the nature of the solid face and dependent only on chemical type, varying from one chemical series to another. The parameter b, on the other hand, is dependent upon the nature of the solid face as well as upon the chemical series.

From the above expression one might expect the coefficient of friction for two dissimilar surfaces to be a mean of the coefficient for the two separate surfaces, and Table VIII, from the paper of Hardy and Doubleday, shows how well this expectation is realized.

The addition of a small amount of fatty acid to a mineral oil materially improves lubrication, especially where the bearing surfaces come in contact and the character of lubrication changes from the complete type to the boundary type. The higher efficiency of boundary lubrication obtained in this way is due to the adsorption of a fatty acid film of high molecular weight on the bearing surfaces.

The qualifications of a lubricant for use in a scientific instrument often depend primarily upon the ability of the lubricant to form stable films which cover the surface of the

TABLE VIII

COEFFICIENTS OF FRICTION

Slider	Plate	Lubricant: Butyl Alcohol	Lubricant: Amyl Alcohol	Lubricant: Octyl Alcohol
Glass	Glass	0.606 } mean	0.585 } mean	0.5176 } mean
Steel	Steel	0.3924 } 0.4992	0.375 } 0.48	0.2981 } 0.4078
Glass	Steel	0.493	0.48	0.41
Glass	Glass	0.606 } mean	..	0.5176 } mean
Bismuth	Bismuth	0.30 } 0.453	..	0.25 } 0.3838
Bismuth	Glass	0.451	..	0.38
Steel	Steel	0.3924 } mean	..	0.2981 } mean
Bismuth	Bismuth	0.30 } 0.3464	..	0.25 } 0.274
Bismuth	Steel	0.348	..	0.27

Hardy, W. B., and Doubleday, Ida, *Roy. Soc., Proc.*, *100A*, 564 (1921–1922).

metal and produce a diminution of static friction between sliding metal parts. Oils which are rich in vegetable or animal fats are superior to petroleum oils in this regard. Hydrated lanolin is an excellent lubricant for sliding friction heads in which a low starting (or static) friction is important. Unfortunately, it is somewhat corrosive.

Colloidal graphite added to oil is similarly adsorbed on bearing surfaces. It is useful for the lubrication of spectrometer cones and, in machinery, it is especially useful for the running-in operations to form a hard polished Beilby layer on the bearing surfaces.[23]

For extremely heavy-duty lubrication, mutton fat or Dutch grease is recommended. Dutch grease is simply a combination of mutton fat with heavy petroleum oils.

It is desirable for clocks and other delicate mechanisms to have an oil that is chemically stable, does not corrode the metal parts, does not escape by spreading or evaporating, and does not freeze easily.

[23] Finch, G. I., "The Beilby Layer," *Science Progress*, *31*, 609 (1937).

The oils from the head and jaw of the porpoise (Nye watch oil) and blackfish satisfy these qualifications most completely. These oils, however, are quite expensive ($125.00 a gallon). Sperm oil is next in quality.

Soap is a good lubricant for wood. Water is used between rubber and metal surfaces. Talc is often used as a dry lubricant for nailing and so forth. Also, graphite, especially colloidal graphite, forms a good dry lubricant at ordinary and elevated temperatures. It is used for lubricating lock barrels. Colloidal graphite dispersed in water or glycerin has film-forming properties which recommend it for some applications. The glycerin dispersion is useful at low temperatures.

Soapstone.[24] When soapstone, or massive talc, is heated to 500°C., it gives off absorbed water. Heating it to 850°C. drives off the remaining water, and finally heating to 1300°C. gives a complete transformation of the mineral constituents. When the material is transformed, the corresponding overall change of hardness is from 1 to 6 on Moh's scale. Owing to these properties, soapstone is very useful in the laboratory, since it can be easily machined before it is fired, and after it is fired it gives a hard material having many desirable properties. The shrinkage from firing is less than 1 per cent. Firing from 24 to 48 hours at 1100°C. is the usual practice. It is said that a material with iron content is not suitable for use in a vacuum, since it gives off gas. Imported Italian soapstone is exceptionally free from iron impurities and is obtainable in large blocks.[25]

Finely divided talc can be pressed and fired at 1400°C., giving a sintered body like that obtained from the massive mineral. The shrinkage of the powder on firing is about 8 per cent. After firing, it has the property that it is not attacked by acids or alkalies. It can be welded to glass.

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[24] Hughes, H. H., *Bureau of Mines, Inf. Circ.*, No. 6553 (1931).
Ladoo, Raymond B., Bureau of Mines, Bull. 213, pages 80–81.

[25] Soapstone is obtainable from M. Kirchberger and Company, 1425 Thirty-Seventh Street, Brooklyn, New York.

Talc, both fired and unfired, is chemically inert; it is not attacked by acids (except slowly by hydrochloric acid) or by alkalies. Fig. 14 shows the electrical resistance of talc and some other refractory materials as a function of temperature.

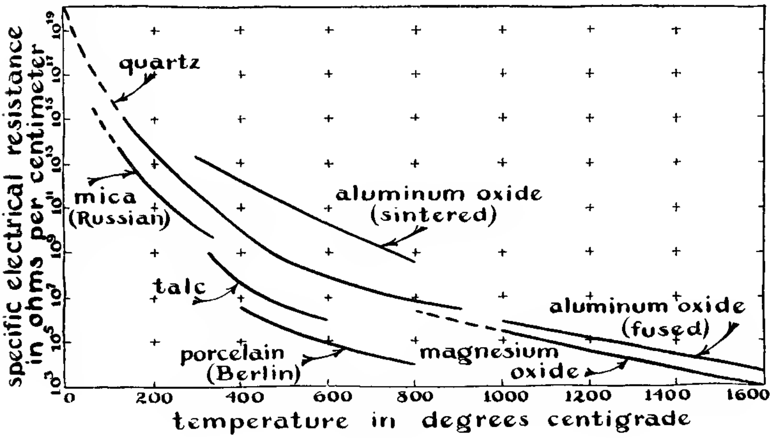


Fig. 14.

Espe, W., and Knoll, M., *Werkstoffkunde der Hochvakuumtechnik*, page 199. Berlin: Julius Springer, 1936.

CHAPTER XIV

Notes on the Construction and Design of Instruments and Apparatus

The cutting of metals. In essence, the cutting of metal in the lathe, the milling machine, and so forth, amounts to the continuous driving of a hard-metal wedge, the tool, under the surface layer of the work. Fig. 1 illustrates a typical tool. In the lathe the work moves and the tool is stationary, while in the milling machine the opposite is the case. This difference, however, is immaterial. The important factors are the cutting angle, the rake, the clearance, and the speed and feed with which the cutting operation is carried out.

The cutting angle is illustrated in Fig. 1. For hard and brittle metals it is best to have this angle large; for soft

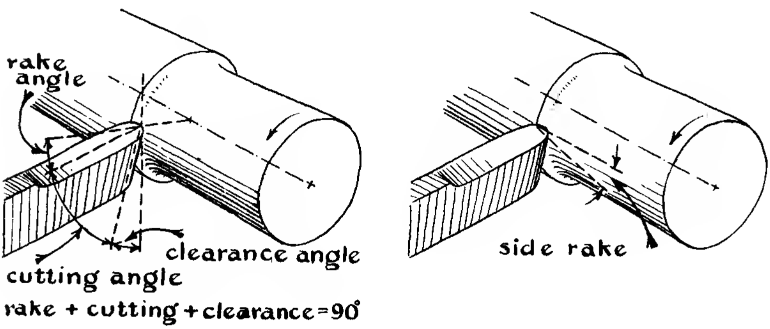


Fig. 1.

tenacious metals it is best to have the cutting angle small. For example, the cutting angle usually varies from 75° for brass and cast iron to 40° for steel and even less for copper

and aluminum. Thin, keen tools with a small cutting angle will not stand up under severe cutting conditions as well as the blunt ones, because the blunt tools conduct heat away from the tip more effectively.

The rake angle is illustrated in Figs. 1 and 2. The dimension of the rake angle determines the amount of deformation or cold working of the metal chip removed. This cold working is diminished, and the heat generation is also diminished when the rake angle is increased. With large rake angles the forces acting between the chip, or turning, and the tool are more tangential than normal. It is desirable to diminish normal forces when cutting soft tenacious metals which tend

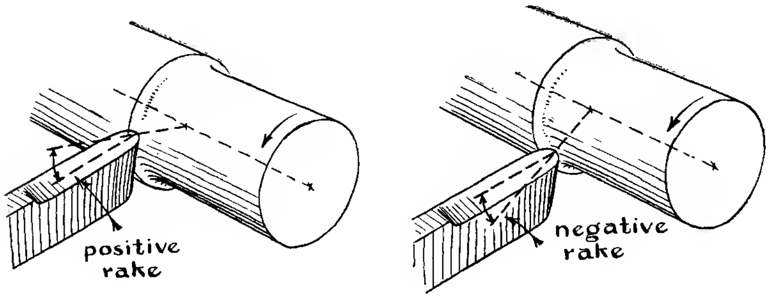


Fig. 2.

to stick to the tool. For brass, the rake angle should be nearly zero—it may be even a little less than zero. (See Fig. 2.)

In the lathe the clearance angle is the angle included between the inner surface of the tool and the direction of relative motion at the tip of the tool. (See Fig. 1.) It is important, especially for boring, to have this angle great enough to prevent the heel of the tool from riding on the work. Clearance angles vary from 35° for soft tenacious metals to 10° for cast iron and brass.

The higher speeds of the lathe should be used for cutting brass except when turning castings or using the cutting-off tool. Unless the proper speed is used with the cutting-off tool, it will chatter. The proper speed and feed for this tool depends upon the size of the work, but in general these

factors are to be determined by trial. A wooden plug inserted in a tube lessens chattering when the cutting-off tool is used. Fig. 3 shows a method of shaping a cutting-off tool which minimizes chattering. In this tool, side rake is balanced against asymmetry of the end so that the tool cuts squarely into the material. The point of the tool is ground on the side of the tool adjacent to the piece on which a finished edge is desired. The other piece may exhibit a slight burr.

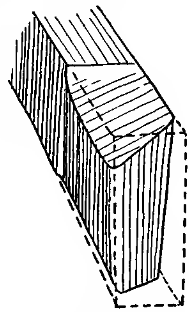


Fig. 3. Cutting-off tool.

For cutting steel, the speed should be as fast as the tool will stand without burning. For final cuts, however, a moderate speed gives a better finish.

Tools with a round nose give smooth finish cuts. Fig. 4 shows such a tool having about 10° clearance for cutting either brass or cast iron. The tool shown here has a slight double side rake, and it will cut in the direction of either the headstock or the tailstock.

The function of a lubricant in cutting metals is in most cases primarily to cool the chip and tool to prevent sticking. Brass, bronze, and cast iron may be machined dry (except in the operations of tapping, knurling, and polishing, for which machine oil is used). Soluble oil or lard oil is used for tenacious metals such as steel. Kerosene or turpentine is often used for aluminum. Milk may be used for copper. Lead and babbitt are turned dry, but they are oiled for filing, drilling, and threading.

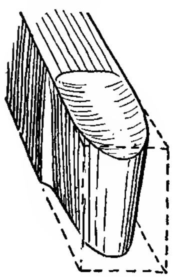


Fig. 4. Finishing tool.

The lathe.[1] The lathe is by far the most versatile machine in the shop. It can accomplish nearly all the operations that are done on other machines, such as the miller, the shaper, the grinder, the drill press, and so forth, besides the

[1] By Roger Hayward.

many operations which it alone can do. For this reason it seems right that we should devote some space to a discussion of its properties.

The essential parts of the lathe are the spindle, tailstock, saddle (or carriage), ways, slide rest, and compound rest. The spindle is supplied with power and rotates in close-fitting bearings, which constrain it to turn on a single fixed axis. The tailstock is a socket, the axis of which is supposed to coincide with the axis of rotation of the spindle. It is mounted on guides in the ways so that its distance from the end of the spindle may be fixed to suit the work at hand. The saddle, or carriage, is used primarily to support a cutting tool and to allow it motion parallel to the axis of rotation of the work. The ways are metal guides on which the carriage and tailstock move. Thcy are formed on the bed, or framework of the lathe, and arc supposed to be parallel to the axis of the spindle. The slide rest consists of ways with a slide. Its ways are supposed to be perpendicular to the axis of rotation. It is mounted on the saddle, and serves to adjust the distance of the tool from the axis of the spindle. The compound rest also consists of a set of ways with a slide. It is mounted on the slide rest and can be adjusted to move the tool that it carries in any horizontal direction with respect to the axis of the spindle.

Lathes are usually equipped with two chucks, one with three jaws and the other with four. In the three-jawed chuck the jaws are moved by the rotation of a spiral or scroll within the body of the chuck. This system is mechanically very poor. The jaws never approach the center at the same rate. As a consequence, round objects mounted in it are seldom accurately centered. If the chuck will center work within 0.003 of an inch, it is about all that can be expected. The three-jawed chuck is good only for work in which all the surfaces are to be turned at one setting, the work then being cut off. Once the work is removed from the chuck, it is practically impossible to replace it concentric with the surfaces already done.

In the four-jawed chuck the jaws are capable of independent adjustment. Therefore the accuracy of the centering of the work in a four-jawed chuck will depend upon the skill of the mechanic. With a dial indicator, and a little practice, work can be centered within 0.0002 of an inch in 5 or 10 minutes. The four-jawed chuck can also be used for holding eccentric or irregular work.

A dial indicator is a measuring device which can be mounted on the tool post in such a way that a projecting lever or plunger will bear against the work as it turns. The dial then indicates the eccentricity of the work directly in thousandths of an inch. It can be supplied with attachments for reaching into holes. It is sometimes desirable, however, to center a piece of work on a prick-punch mark. In this case a pencil with a rubber eraser in its end may be used. The tip is inserted in the prick-punch mark, and the eraser is placed in the tailstock. The indicator is then placed to bear against the pencil, and as the work is rotated, it shows the eccentricity of the punch mark.

The primary operation which a lathe can perform is to execute a truly circular cut on a piece of material. This operation is accomplished by mounting the work directly on the spindle, or by mounting it between the spindle and the fixed bearing in the tailstock, so that it can be rotated against the tool. The perfection of roundness of the work depends in either case upon the perfection of the spindle bearings. If the spindle wabbles, the tool cut is, of course, not true.

The tool is mounted so that it can be moved in a horizontal plane passing nearly through the rotation axis. As the work rotates, the moving tool makes a continuum of circular cuts. These generate, in general, a conical surface. Of the possible cones two are of special interest in machine work: one, that of zero taper, is the cylinder, and the other, that of infinite taper, is the flat surface produced by a facing cut. All others come under the head of taper cutting.

Generation of a cylindrical surface is possible if the tool

moves truly parallel to the axis of rotation of the work. In practice this is never the case, although in good lathes the error is usually negligible. When the work is mounted on the spindle, this parallel motion of the tool in respect to the axis is possible only if the ways of the carriage are parallel to the spindle, and if the ways themselves are straight. They are usually quite straight in the horizontal sense, but in the vertical sense the wearing of the ways tends to make them concave, with the result that the carriage moves up and down as it travels. For this reason it is always desirable to have the tip of the tool at the same height from the ways as the axis of rotation, for the error introduced by its up and down motion is then minimized.

If the work is mounted on dead centers, that is, if it is supported on conical points between the spindle and the tailstock and is turned by a dog bearing on the face plate, then truth of the work depends upon parallelism of the ways to a line between the two points, or centers. The tailstock is usually in error. It may be out of line laterally, a fault that one can usually correct by taking a trial cut, measuring the two ends, and setting the tailstock over again, using the adjusting screws which are usually provided. If the tailstock center is too high or too low, there is little to be done except to keep the tool at the average height of the two centers, thus minimizing the errors. Sometimes the ram, or plunger, in the tailstock which carries the center does not move parallel to the axis of the spindle. Thus, it may be well centered when the ram is retracted but not when the ram is extended. Sometimes the tip of the dead center, that is, the center in the tailstock, is bent or worn, in which case the remedy is obvious. If the live center, the one in the spindle, is untrue, it makes no difference unless the work is to be reversed and further machined. The live center is usually of soft steel, and for nice work it is common practice to true it by turning down its tip before mounting the work.

One way to turn a cylinder of uniform diameter is to lash the work to the face plate with thongs and to support it

with a follower rest mounted on the carriage directly opposite the tool. This practice will insure uniformity of diameter but will not insure the straightness of the work. Sometimes in machining slender objects, one end of the work is held in a chuck while the other end is supported by the tailstock. This is bad practice, for the removal of the material from the work may relieve internal stresses, especially in cold-rolled steel and in rolled or drawn brass. As a result, when the work is removed from the lathe, it is found to be bent, the tailstock having supported the work in a flexed condition. The better practice is to support the work between centers, using a follower rest to prevent flexure. Occasionally, a second tool is mounted on the opposite side of the work and in an inverted position. This serves to preserve the uniform diameter of the work. In thread cutting it can also serve to reduce the drunkenness of a long screw thread, but it obviously requires very accurate setting of the two tools.

In boring cylindrical holes, if the work is mounted on the spindle, the truth of the work is solely dependent upon the truth of the ways. If the work is mounted on the carriage, however, a boring bar can be threaded through the rough bored hole and mounted between dead centers. A tool mounted on this bar describes a very nearly perfect circle, and as the work is fed over it, a hole of uniform diameter is automatically generated. The straightness of the ways determines the straightness of the hole, but parallelism (or the lack of it) of the ways to the axis of the spindle or to the axis of the boring is of no moment. For short holes a fly cutter may be mounted on the spindle, and the result will be the same as with a boring bar. In most work which can be mounted on the spindle the hole is bored to almost the required size, and then a reamer is passed through it to bring it to size and uniform diameter.

In turning long tapers, a taper attachment should be used, if one is available. If not, the work is mounted on dead centers, and the tailstock is set over the proper amount. The angle of taper is a function of both the amount of the

setover and the length of the work. Since the length of the work, that is, the distance between the points where the axis of the work intersects the axes of the headstock and the tailstock, cannot be accurately measured, it is impossible to predetermine the exact angle of the taper which will be cut. Consequently, the amount of setover of the tailstock must be determined by trial.

The compound-slide rest is used to cut short tapers. It is usually the least accurate feature of the lathe, so that high

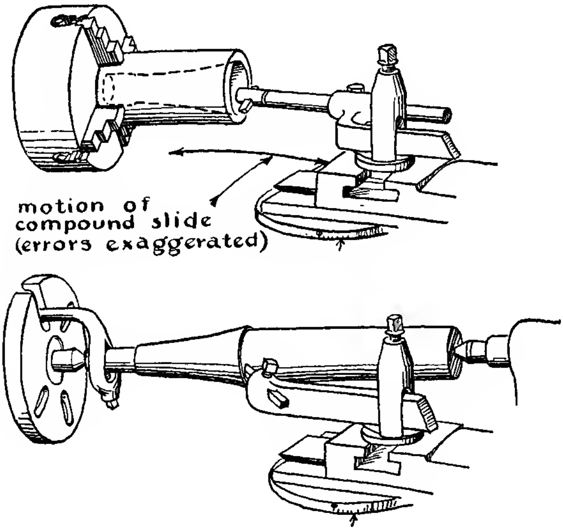


Fig. 5.

precision with it is not to be expected. The graduations which are used to determine the angle of motion are generally very inaccurate and should be regarded only as something on which to base an estimate. The slide, because of its shortness, is usually not straight. It can nevertheless be used successfully for turning and boring short tapers to match, such as for lug valves and stopcocks, since the errors of curvature can be made to match. The female part is first mounted on the spindle, and the tapered hole is bored with the boring tool cutting on the far side of the hole, the

lathe running backwards. When this is done, the face plate or chuck holding the piece should be removed bodily from the lathe, leaving the work undisturbed. This will permit the replacing of it for further operations, if necessary, without having to recenter the work. The male taper is then mounted, preferably between dead centers, and turned, the compound rest being used as it was set for boring, thereby insuring that the tapers will match. If the slide is not straight, the tool should be set so that its tip overhangs the slide as much as did the boring tool for the female part. If the same part of the slide is used, the errors in one taper will match those of the other. The male part, being on dead centers, may be removed from the lathe and tried in the female part and replaced for further machining, until the desired fit is obtained. For the final fit they should be lapped together with Bon Ami or some other suitable abrasive. (See Fig. 5.)

We cannot go into the arts of filing and scraping. They are treated in many of the standard works on machine practice and tool making. Filing and scraping afford the machinist opportunity for the fullest display of his manual skill. Both are, like the figuring of an optical surface, a process of delicate testing alternated with the careful manual removal of metal in order to obtain the desired surface. In filing, the testing is usually executed with the ordinary measuring instruments—the straightedge, the square, and the calipers. In scraping, the testing is done with Prussian blue, and always the two parts are scraped until an intimate and complete contact between them is obtained. Testing flats are made three at a time. The three plates are each scraped until any one of them will make satisfactory contact with either of the other two.

From the above discussion it will be noted that the limits of accuracy characteristic of the different operations can be roughly classified. There are, on the one hand, operations such as the generation of a circular cut, or the fitting of a taper to a cone by lapping, which are automatically accurate

to a high degree. There are other operations which depend upon the truth built into the machine, for example, the cutting of a straight cylinder in a lathe or the milling of ways. Finally, there are those operations which depend upon the skill of the machinist. Examples are the mounting of work in the machine in order to have new cuts consistent with former ones, and the execution of filing operations to a line. There are many opportunities for the machinist to use his ingenuity to advantage in the attainment of precision. We have already mentioned examples in which the cuts on work in the three-jawed chuck are all done at one mounting, and in which the same part of the compound-slide ways are used for cutting male and female tapers, and so forth.

Soft soldering. Good soldered joints require thorough cleaning and, in addition, the use of a so-called "flux." The function of the flux is to etch the surface free of contamination and protect it, as well as the solder, from oxidation.

The most useful flux for soft soldering is made from a mixture of 2 parts zinc chloride to 1 part ammonium chloride dissolved in a minimum amount of water. This flux is often spattered about when the soldering copper is applied, and unless it is thoroughly removed, it promotes corrosion, especially on iron. If the work is washed with soda solution, the corrosive action of zinc chloride and acid flux is, in large measure, neutralized. In addition to corrosion, the spattered flux may also give rise to electrically conducting surface layers on parts of the apparatus where high insulation is required. For such work, a solution of rosin in alcohol is an excellent nonconducting flux (for soldering copper wires). Also, so-called noncorrosive pastes are available at most hardware stores. These are made from vaseline (90 per cent) and ammonium chloride (10 per cent).

Three things are needed for successful soldering. In addition to cleanliness and flux, sufficient heat is required. Some soldering is done entirely with a flame, while some is done entirely with a soldering copper. However, the nicest jobs are done with a combination of these, especially when

the work is on complicated apparatus and when several relatively large parts are to be joined together. A soft flame played over the surface of the whole work supplies basic heat, keeping the work at a temperature of 125° to 150°C. The higher temperature that is required for soldering is then obtained locally by the application of the hot soldering copper. This soldering procedure minimizes the danger of melting off parts previously joined, a possibility to contend with when a flame alone is used. Also, the amount of solder added and the extent to which the solder flows is more easily controlled with the soldering copper than with a flame alone. On the other hand, the use of a flame to supply basic heat facilitates heating with the soldering copper and increases the effectiveness with which the molten solder can be made to wet the work and flow as desired.

A seam to be soldered is first "tinned" at a high heat, and then at a lower temperature a fillet is made with the help of the soldering copper. The purpose of the fillet is to insure that the solder does not draw away and allow an opening to form in the seam as it cools. Fig. 6 shows how a recess cut in an inconspicuous place will serve the same purpose as a fillet.

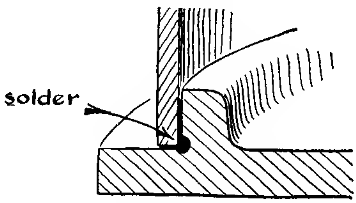


Fig. 6.

Many of the alloy steels, as well as cast iron, magnesium, aluminum, tungsten, and molybdenum, cannot be easily soft-soldered.

Hard soldering. Although there are some intermediate solders which melt at temperatures between the melting temperatures of soft solder and silver solder, they have never had wide use. These solders may be useful in special cases, but for general work they do not have the reputation of silver solder, which, for strength, ductility, wetting power, penetration, and resistance to corrosion, is unsurpassed.[2]

[2] Especially good for hard soldering is Easy-flo solder (M.P. 620°C.), manufactured by the Handy and Harman Company, Bridgeport, Connecticut.

The heat for silver soldering is obtained with the oxy-acetylene torch for large work and with an air-gas or oxygen-gas torch for small work. The metal to be soldered is preheated, with the application of the flame favoring those parts which are most massive and which have the highest heat conduction. A general preheating of the whole work prevents warping and also facilitates the intense final heating of the joints that are to be brazed.

The regions to be wet and joined by the silver alloy are painted with a thin paste mixture of 5 to 10 parts of powdered borax, 1 part powdered boracic acid, and water. Dry borax can also be used. The use of paste has the advantage of neatly defining the areas which will be wet with the alloy. The alloy will spread over the surface only to the extent that it has been brushed with the paste. The flux for stainless steel is made from 1 part borax and 1 part boracic acid, and these powders are wet with a saturated zinc chloride solution.

For large work the silver solder is applied in the form of wire or rod after the work is well fluxed and has attained the proper temperature. The solder wire should also be coated with flux. For small work small pieces of silver solder, either short lengths of wire or bits of sheet solder, may be applied, together with flux, before the work is heated. When the parts to be joined fit together neatly, only a film of the silver solder is needed to give a good joint. The use of more solder is wasteful. Charcoal (medicated so that it does not burn) and asbestos blocks can be used for holding the work and for proper positioning of the parts to be joined. (See Fig. 7.)

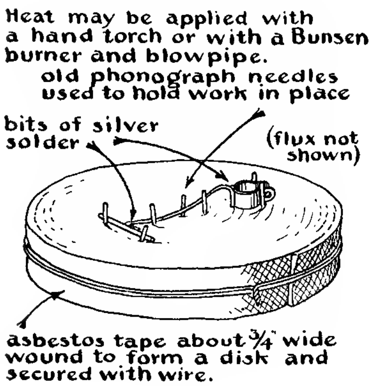


Fig. 7.

After the joint is made, the flux is best removed by quenching the work in cold water. This procedure is not recommended for large parts or for those requiring high accuracy, since some warping is always produced by quenching. Borax flux will dissolve slowly in hot dilute sulphuric acid in cases in which such treatment can be applied.

Spot welding. Another much-used method of joining metals in the laboratory is spot welding with an electric current. Ordinarily, the spot-welding apparatus obtains its electric energy from a transformer with a capacity of 1 or 2 kilowatts. The primary winding is connected to the alternating-current supply and it is equipped with taps or is connected in series with a rheostat to control the welding current. The secondary winding is usually a few turns of heavy copper wire on rod (about $\frac{5}{32}$ inch in diameter), with the winding ratio such that the secondary delivers about 6 volts. The heavy copper winding terminates at two copper electrodes, which serve to apply the potential to the joint to be welded. The welding is effected by the Joule heat generated between the metal surfaces to be welded when the current is passed in the primary of the transformer for a fraction of a second. The heating produced is regulated by the rheostat and by the length of the time that the switch is closed. The electrodes are brought in contact

TABLE I

ADAPTABILITY OF METALS TO SPOT WELDING

Best	Good	With Difficulty
Nickel to iron	Nickel to $\begin{cases}\text{tungsten}\\\text{molybdenum}\\\text{tantalum}\end{cases}$	Nickel to $\begin{cases}\text{copper}\\\text{aluminum}\end{cases}$
	Iron to $\begin{cases}\text{copper}\\\text{constantan}\end{cases}$	Iron to $\begin{cases}\text{tungsten}\\\text{molybdenum}\\\text{tantalum}\end{cases}$
		Aluminum to aluminum

All other metals are spot-welded with difficulty (except with a protecting atmosphere and thyratron-controlled current pulse).

with the work, and a definite pressure is applied, usually by means of a foot pedal. The pressure and duration of the current are important. Inadequate pressure results in burning and "spitting" at the joint, while too much pressure decreases the joint resistance and consequently the heating action.

Metals which weld together best are those of similar melting temperature T_m°C. and heat conduction K. Table I shows the relative spot-welding characteristics of the different laboratory metals as determined by Espe and Knoll.[3]

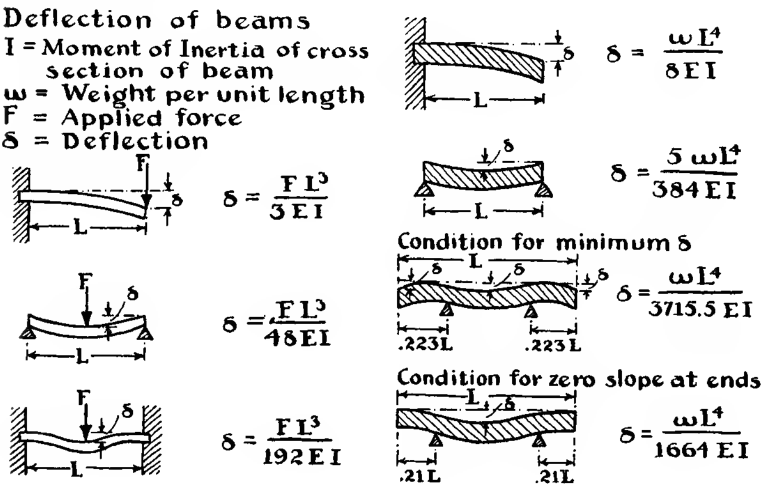


Fig. 8.

See Wright, W. H., *Pub. Lick Obs.*, *9*, 50 (1907).

Wires with different melting temperatures and heat conductivities weld together best when their diameters d are related as follows:

$$\frac{d_1}{d_2} = \frac{K_2}{K_1}\sqrt[3]{\frac{T_{m_1}^2}{T_{m_2}^2}}. \tag{1}$$

Instrument design. *Deflections.* The subject of instrument design is one to which a great many authors have

[3] Espe, W., and Knoll, M., *Werkstoffkunde der Hochvakuumtechnik.* Berlin: Julius Springer, 1936.

given their attention. We will treat of the general aspects of the subject, such as the application of the principle of kinematical design and the calculation of deflections and flexures as they pertain to instruments.

When an element of an instrument is subjected to varying forces that are due to uneven friction between the moving parts, the designer must be able to determine the effect of these variations.

Such problems are often difficult to solve precisely, owing to the complex geometry involved. However, it is often sufficient for the designer to know the answer to within 50 or 100 per cent. Estimations to this accuracy are often possible if one makes an ingenious choice of a simple geometric shape whose deflection may be taken as a first approximation to the deflection of the part in question. The formulas for determining the deflections of the simple geometrical shapes, variously loaded and supported, are given in Fig. 8. The moments of inertia of the cross section of beams about the axis passing through their center of gravity are required for these calculations. The moments of inertia for rectangular bars, rods, tubes, and I-beams are given in Fig. 9.

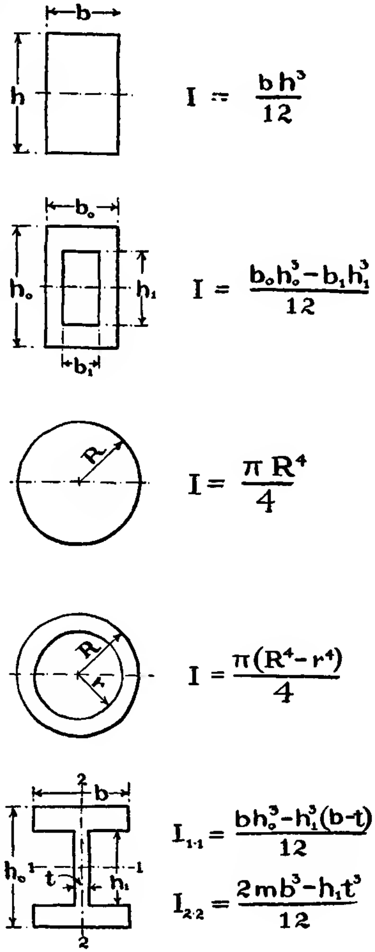
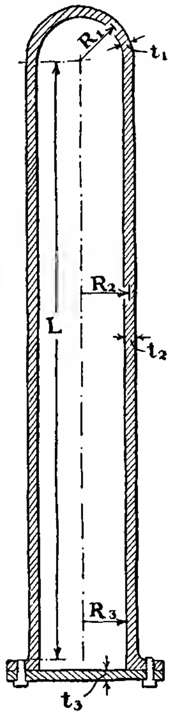


Fig. 9. Moments of inertia of other sections can be found in mechanical-engineering handbooks.

Fig. 10 gives the formulas for calculating the collapsing pressures for spherical and cylindrical shells and plane circular plates loaded with an external pressure. These formulas are useful for designing vacuum tanks.

In making apparatus, the physicist seldom needs, for reasons of economy, to limit the mass of the instrument.



δ = Deflection
ΔR_o = Eccentricity of a tube
E = Modulus of elasticity
P = Pressure
P_{crit} = Theoretical collapsing pressure
ρ = Poisson's ratio
σ_{yp} = Fiber stress at yield point

Collapsing pressure for a hemispherical end

$$P_{crit.} = \frac{2Et_1^2}{R_1^2\sqrt{3(1-\rho^2)}}$$

Collapsing pressure for a cylindrical tube where $L \geqq 20R_2$

$$m = \frac{R_2}{t_2} \qquad n = \frac{\Delta R_o}{R_2}$$

$$P_{crit} - \left[\frac{\sigma_{yp}}{m} + \frac{(1+6mn)E\,t_2^3}{4(1-\rho^2)R_2^3}\right]P_{crit} + \frac{\sigma_{yp}\,E\,t_2^3}{4m(1-\rho^2)R_2^3} = 0$$

Theoretical limiting pressure for a circular end plate clamped at its edges.

$$P_{crit} = \frac{4\sigma_{yp}t_3^2}{3R_3^2}$$

Deflection at center for a circular end plate clamped at its edges

$$\delta = \frac{3PR_3^4(1-\rho^2)}{16\,E\,t_3^3}$$

Theoretical limiting pressure for a circular end plate unclamped

$$P_{crit} = \frac{8\sigma_{yp}t_3^2}{3R_3^2(3+\rho)}$$

Deflection at center for a circular end plate unclamped

$$\delta = \frac{3PR_3^4(1-\rho)(5+\rho)}{16\,E\,t_3^3}$$

Fig. 10.

Timoshenko, S., *Theory of Elastic Stability*. New York: McGraw-Hill Book Company, 1936. See also "Proposed Rules for the Construction of Unfired Pressure Vessels Subjected to External Pressure," *Mechanical Engineering*, April, 1934. Graphical solutions are given in this reference for short as well as long tubes.

Accordingly, for the construction of spectrometers and other instruments, which require very accurate relative positioning of the various elements, the physicist often uses an **I**-beam of generous proportions and excessive strength. If the instrument is a spectrometer, one or more of the faces of the **I**-beam are planed to afford a base for the mounting of lenses, slits, and a prism or grating table.

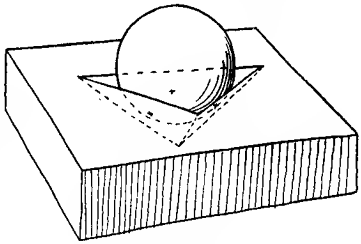


Fig. 11.

Kinematical design.[4] The different ways in which the principle of kinematical design may be used for positioning the various elements of an instrument are illustrated by Figs. 11 to 23.

According to the principle of kinematical design, a body must have at least $(6 - n)$ points in contact with a second reference body if it is to have only n degrees of freedom, relative to the reference body. Fig. 11 shows a spherical ball held in a trihedral cavity in a plate by the force of gravity. Relative to the plate, the center of the ball is uniquely defined by the three contacts with the plate. There remain three degrees of freedom of rotation for the ball about three mutually perpendicular axes.

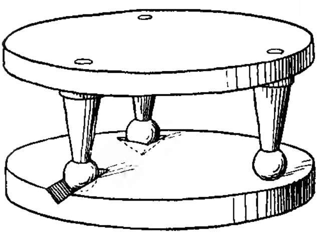


Fig. 12.

The principle of kinematical design is further illustrated by Fig. 12, which shows a tripod with a ball at the extremity of each of its legs. The plate on which the tripod rests has a **V**-groove and a trihedral cavity in its surface. One ball rests in the cavity, the second in the groove, and the third

[4] See the following:

Pollard, A. C. F., *The Kinematical Design of Couplings in Instrument Mechanisms.* London: Adam Hilger, Ltd., 1929.

Whitehead, Thomas North, *The Design and Use of Instruments and Accurate Mechanism.* New York: The Macmillan Company, 1934.

on the plane surface of the plate. When one of the balls is in the trihedral cavity, then, as far as translations are concerned, the tripod may be regarded as fixed by the three points of bearing between the ball and the sides of the trihedral cavity. If, however, a second foot rests in the V-groove, there are two more point contacts between the ball and the sides of the groove. The tripod is now restrained by five point contacts and has, accordingly, one degree of freedom, which is a rotation about an axis passing through the centers of the constrained balls. The tripod's position is finally completely determined when the third leg comes to rest on the plane, giving the sixth point of contact.

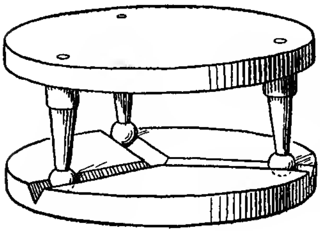


Fig. 13.

Fig. 13 shows another way in which the tripod may have its position uniquely defined relative to a base plate. Here the terminal balls of the tripod legs rest in radial grooves machined in the plate. Each ball makes two contacts with the base plate, making a total of six contacts.

These applications of kinematical design are often useful, as, for example, when the base plate is attached to an instrument and the tripod carries some element which must be repeatedly removed and replaced in exactly the same position. The application shown in Fig. 13 has the advantage over the one shown in Fig. 12 that the centers of the table and the base plate have the same relation to each other laterally, independent of difference in their temperature expansion.

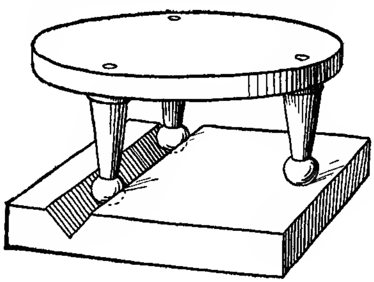


Fig. 14.

Fig. 14 shows a case in which one degree of freedom, that is, of translation, is achieved by placing two balls in V-

grooves, with the third on a flat surface. Five contacts between the plate and the tripod are involved.

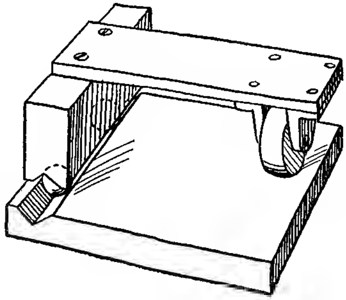


Fig. 15.

Other examples of the achievement of one degree of freedom by five appropriate contacts are shown in Figs. 15 to 19. The method shown in Fig. 15, and especially Fig. 16, is often used for typewriter carriages.

Figs. 17 and 18 are more or less self-explanatory. In Fig. 17 gravity acts as the so-called locator. The locator, as its name implies, insures that the bearing points remain in contact. The arrangement shown in Fig. 18 is used by the Leitz Company for the vertical motion of their microscope tube.

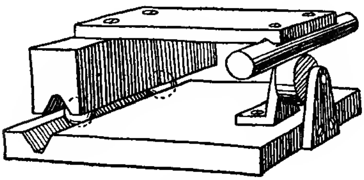


Fig. 16.

Fig. 19 shows a simple and easily constructed device used to move a Foucault testing knife edge. Its design is kinematical.

In most of the examples given here the contacting areas are small. Accordingly, the wear on them may be great. Often, in practice, point contacts are extended to line contacts as shown in Figs. 20, 21, and 22. Or, point contacts may be extended to surface contacts, as shown in Fig. 24. Even so, one still retains substantially all of the virtues of the more rigorous type of design, where contact areas are small. And, in addition, wear is materially reduced.

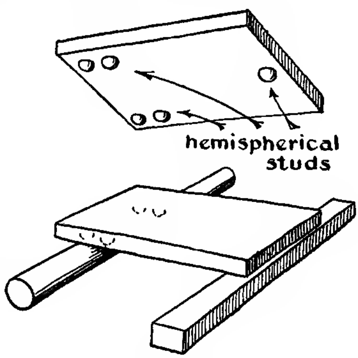


Fig. 17.

Fig. 20 shows how one degree of freedom is achieved for focusing the reading microscope of the Cambridge Instrument Company's comparator.

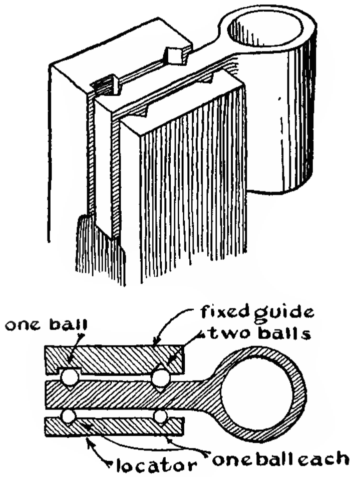


Fig. 18.

Fig. 21 shows a type of support which might be used for an optical bench. For example, with it a lens holder may be moved back and forth along two horizontal rods and clamped at any desired position.

Fig. 22 illustrates how one degree of rotation may be obtained. The rod involved here may also translate along its axis unless a constraint is applied, as, for example, a fixed ball in contact with the end of the rod.

Fig. 23 shows how geometrical design may be applied to a tangent screw.

Generally, the construction of an instrument is easier if the design follows the kinematical principle than it is when

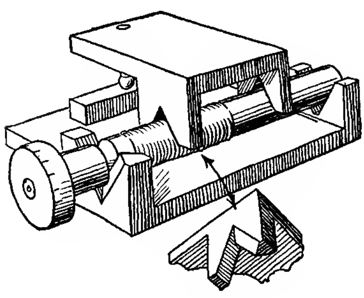


Fig. 19.

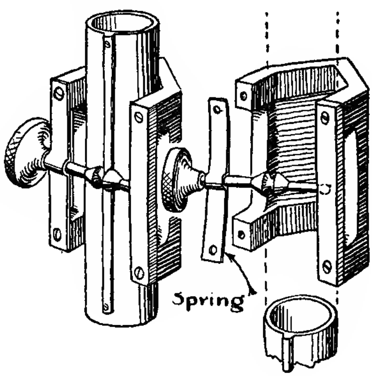


Fig. 20.

constructed in accordance with the practices of conventional machine design. Conventional designs, in which one uses

cones, ways, and lapped journals to achieve one degree of freedom, either lead to overconstraint in the position of the parts or they are not uniquely defined. Only five contacts are required to constrain the parts as desired; any more are redundant, like the fourth leg of a stool.

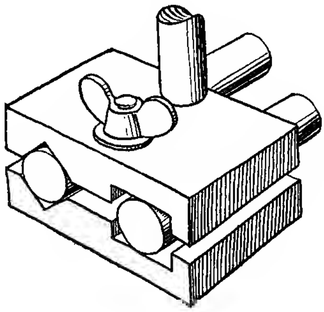


Fig. 21.

Although one degree of translation is achieved easily by following the kinematical principle, as we have seen in Figs. 14 to 21, the conventional cone, when properly lapped, affords a better construction for the achievement of one degree of freedom of rotation.

One feature of the kinematical design which distinguishes it is exemplified by the figures illustrating one degree of translation, such as Fig. 17; although the motion may not be

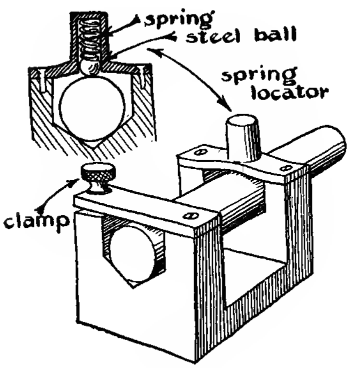


Fig. 22.

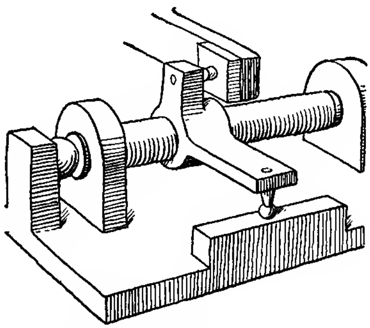


Fig. 23. Here a locator (not shown) will be required to maintain the contacts. A better construction would have the plane, which controls the orientation of the nut, on the opposite side of the screw.

straight, owing to imperfect construction, still it is possible to predict the deviation from straightness from the measured errors of construction.

Steel balls are often used in kinematical design. They

are obtainable matched in size to 0.00005 inch, and in addition they are truly spherical to this accuracy. Precision balls can be obtained which are spherical to within a tenth of the limit mentioned above.

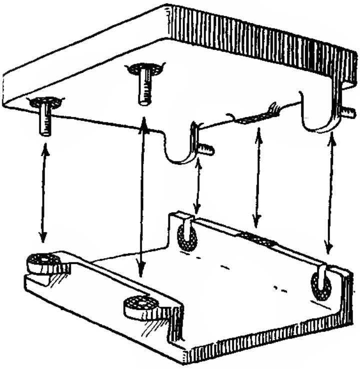


Fig. 24. Semi-kinematical design of the support for the base plate of an instrument. See *The Design and Use of Instruments and Accurate Mechanism,* footnote 4.

Fig. 25 shows a good design of an adjustable mirror cell. It will be noted that this cell has four adjusting screws. Because it facilitates the making of the adjustments, this number is recommended instead of three, in spite of the fact that one of the screws is not needed, and its use leads to strain in the cell.

Vibrationless supports. Many delicate instruments and particularly high-sensitivity galvanometers, must be protected from the vibrations produced by automobiles in the street, elevators, machinery in the basement, and vibrations from other sources which are always present in a building. In most cases, the vertical components of these vibrations

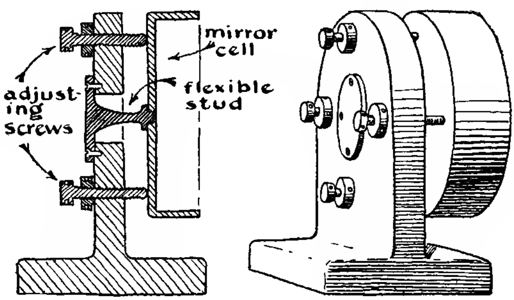


Fig. 25.

are harmless and can be ignored. Although the effect of the horizontal components on an instrument such as a galvanometer may be small, especially if the moving system is

dynamically balanced on its suspension fiber, it is, however, necessary for the most delicate work to eliminate these horizontal components as far as possible by mounting the instrument on a vibrationless support.

The problems involved in obtaining a suitable support are similar to some of the problems encountered in designing a seismograph, and anyone planning to develop a special vibrationless support of his own design will find the literature on seismographs helpful. Briefly, all vibrationless supports can be considered as an oscillating system loosely coupled mechanically to the walls, ceiling, or floor of the room. The shielding effect of the support is determined by the resonance between it and the wall. For example, if the natural period of oscillation of the support is long compared to that of the vibrations of the wall, it will be so far out of resonance that its response will be feeble. It is, of course, necessary that the support be damped so that its own natural oscillations will be suppressed. Also, it must be protected from air currents. Naturally, one selects the most stable place for mounting the vibrationless support. A pier which has a separate foundation from the rest of the building is ideal.

A modification of the Julius suspension has been designed by R. Müller.[5] This suppresses only the horizontal vibrations. A simplified construction of his design, which has been used successfully by the author, is shown in Fig. 19, Chapter VIII. The support is loaded so that it has a period of about 2 seconds. This support uses the internal friction of oil in pie pans to dampen it. Light oil is used, and the pans are filled to the height which is observed to produce maximum damping of the natural oscillations of the system. The advantages of this support over a Julius suspension are that it can be mounted on a shelf in the corner of the room and easily boxed in to protect it from air currents, whereas a Julius suspension must be hung from the ceiling. It is more difficult to make adjustments of the galvanometer with the Julius suspension than with this support, because the Julius

[5] Müller, R., *Ann. d. Physik*, *1*, 613 (1929).

suspension is not easily clamped. The Müller support can easily be clamped for making adjustments of the galvanometer by dropping two tapered pins in the holes indicated in the figure.

One type of vibrationless support is made by placing a large mass, say a slab of stone, on a pile of newspapers. Here the shearing friction in the papers damps horizontal oscillations. Another method involves supporting the machine by steel springs wound with friction tape for damping.

Other methods of eliminating vibrations involve supporting apparatus on tennis balls or sponge rubber. These are particularly useful for stopping vibrations near their source, as, for example, preventing vibrations from vacuum pumps from being transmitted into the walls and floor of the building. The damping in this case is due to the internal friction of the rubber.

CHAPTER XV

Molding and Casting

BY

ROGER HAYWARD

PROCEDURE in molding and casting metals has changed very little since the beginning of history. There have been changes in the attendant mechanism, but the essential methods are the same as those used by prehistoric man. Because the casting of metals seemed a wonderful thing to those who did not practice the art, those who did guarded jealously the details of their craft, lest others find out how easy it was.

The object of this chapter is to acquaint the reader with a general working knowledge of the subject. Few laboratories are equipped with facilities for handling molten metals, so that the experimenter will often be obliged to have casts made by commercial foundries; but they are usually equipped for him to make his own patterns from which the casts are made. He will find it economical to do so, for the cost of having the patterns made may be many times the cost of the casts. In order to construct his patterns with intelligence, he should have an understanding of current foundry practice.

The lost-wax method. The methods of casting metals fall into two classes: one, the "cire perdue," or "lost wax," and the other, "sand casting." The lost-wax method consists in burying a wax model, or pattern, in sand and fire clay, and then burning the wax out, leaving the mold ready to receive the metal. This method is employed in sculpture, and in dentistry for the casting of gold teeth, inlays, and so

forth, when only one cast is wanted, for obviously there can be only one cast made from a single pattern. Hence the name "lost wax." The method is useful for making small irregular objects. It is particularly good for casting small parts in gold, silver, or platinum, for ordinarily the experimenter is loath to work such objects from solid metal. He finds it a nuisance to save the chips and filings that are too valuable to lose.

The advantage of the lost-wax method is that the pattern may be of any imaginable complexity. Undercutting or the lack of it is of no importance. The only problem is in the arrangement of gates and risers for admitting the metal and for allowing the air to escape. In the case of hollow sculpture the core is usually supported in the mold by rods of the same metal as that of which the statue is to be cast.

The wax used is a mixture of beeswax and paraffin. This mixture can be procured already prepared at a dental-supply house, or it can be made up readily, for the proportions are not critical. The wax is first softened by being heated until it is pliable; it is then roughly formed with the hands; and after that it is carved into the desired shape (Fig. 1). The carving may be done with any sharp instrument. If the operator cuts away too much, he may replace it by picking up a piece of wax with a pair of tweezers, softening the wax in the flame, and then touching the tweezers to the spot that is to be filled in. The tweezers act much as a ruling pen. Fig. 1 shows the making of a mandrel for winding the spiral tungsten coils used in evaporating metals. This object is taken as an example because the double spiral thread that is required is very difficult to cut on a lathe. As will be seen from the illustration, it can easily be modeled in wax.

Small models are held on the tip of a small rod. To remove the model from the rod, a piece of hot metal is held against the rod until it becomes warm enough for the wax at the tip to melt and allow the model to drop off. A hot-wire tool, such as is described in the chapter on quartz-fiber technique, would be a useful one for this purpose. When

the model is finished, it is stuck on the end of a tapered metal pin, which serves to support the model while the mold is being made, and which, when removed, leaves a channel, or sprue, through which the metal can flow. The object illustrated in Fig. 1 is shown as being modeled directly on

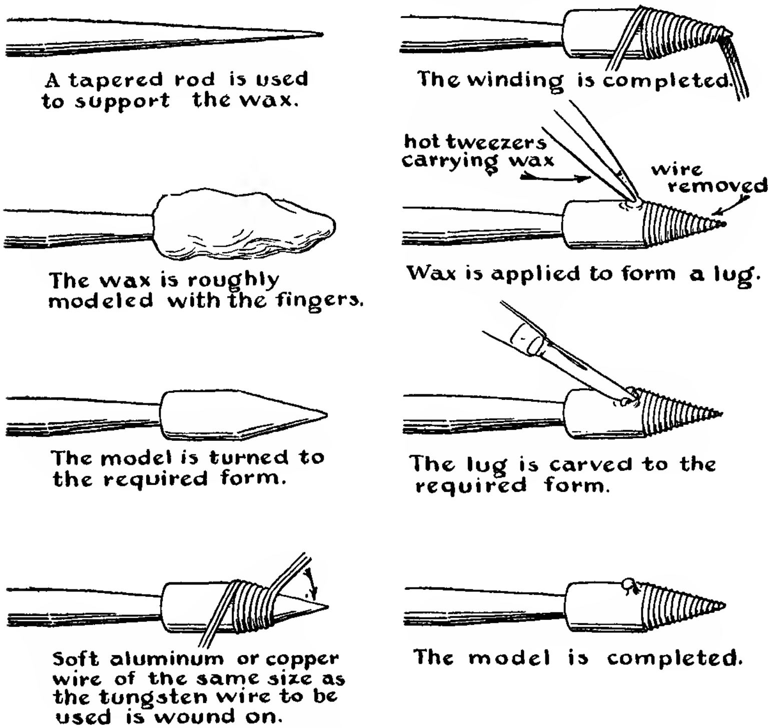


Fig. 1. Lost-wax casting. Making the model.

the tapered rod that also serves to form the sprue. Since the wax alone would hardly be strong enough to stand the winding of the wires that form the threads, the pin is shown as extending to the tip of the model—a procedure peculiar, of course, to the example illustrated.

If the object is to be cast in lead, type metal, babbitt, tin, pewter, solder, or other such metals, the mold may be made of plaster of Paris. If it is to be of gold, silver, copper, brass, or other metals having a higher melting point, the

regular dental investment material procurable at a dental-supply house should be used. This material is mixed with

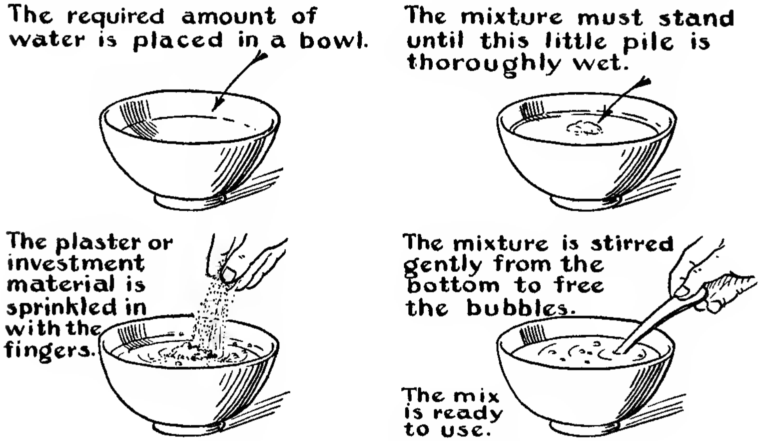


Fig. 2. Proper method for mixing plaster of Paris.

water and sets in about a minute. It should be mixed in the same way as plaster of Paris (Fig. 2): A bowl is partly filled with water, and the investment is sprinkled into the water with the fingers until the level of the investment, which spreads out under the water, reaches the level of the water. Do not stir until all the investment has been added. If there is a little pile standing above the water in the center of the bowl, wait until it is wet, and then stir gently to free any trapped bubbles. (Before starting the mold, oil the pin lightly to prevent the investment from sticking to it.) With a soft brush, paint the outside of the model with the investment and water mixture (Fig. 3). Immediately hold the object in the mold container, and

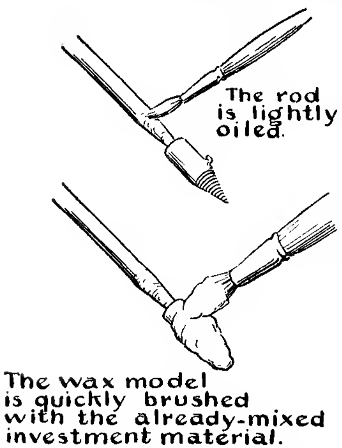


Fig. 3. Lost-wax casting. Preparing the model for the mold.

pour in the rest of the investment. Continue to hold the object until the investment is set (Fig. 4). The mold container should be an iron sleeve. A section of pipe faced off on the bottom in the lathe will do. Dentists use a ring which tapers 5° to 10°, the small end being the bottom. The taper serves to prevent the entire mold from being forced out of the ring and destroyed while the metal is being forced in. This point will appear obvious in a later paragraph, which describes the process of pouring the metal.

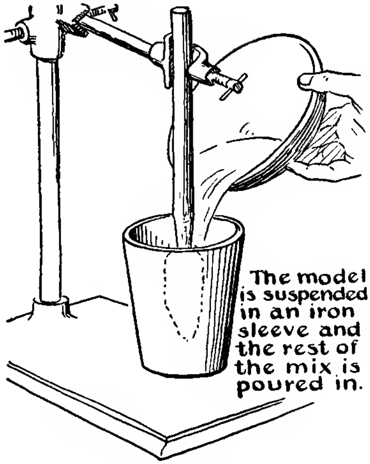


Fig. 4. Lost-wax casting. Making the mold.

As soon as the investment has set, pull out the supporting rod, and around the hole, or sprue, carve a small funnel to receive the metal (Fig. 5). Be careful to remove any bits of material that fall down the sprue. Place the whole thing in a ring stand and heat with a Bunsen burner. Heat until the whole mold is red hot, to make sure that the last traces of wax and moisture are driven off (Fig. 6).

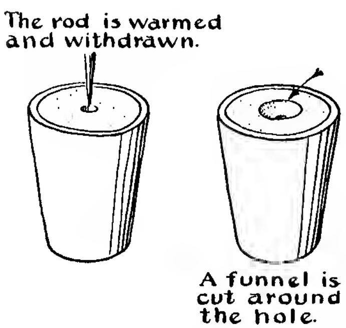


Fig. 5. Lost-wax casting. Making the sprue.

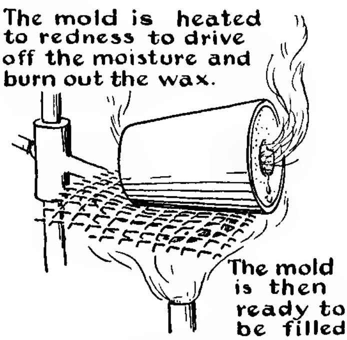


Fig. 6. Lost-wax casting. Burning out the wax.

The mold is now completed and ready to receive the metal. There remains the problem of getting the metal to flow into the mold. When the sprues are tiny and the masses of metal small, the surface tension may prevent the metal from flowing. Also, the trapped air in the mold will be a real obstacle. Dentists use a vacuum method for getting the air out of the mold. A metal disk with a hole in the center communicates with a small tank by means of a pipe. The pipe has a stopcock, which is kept closed until the metal is melted. A

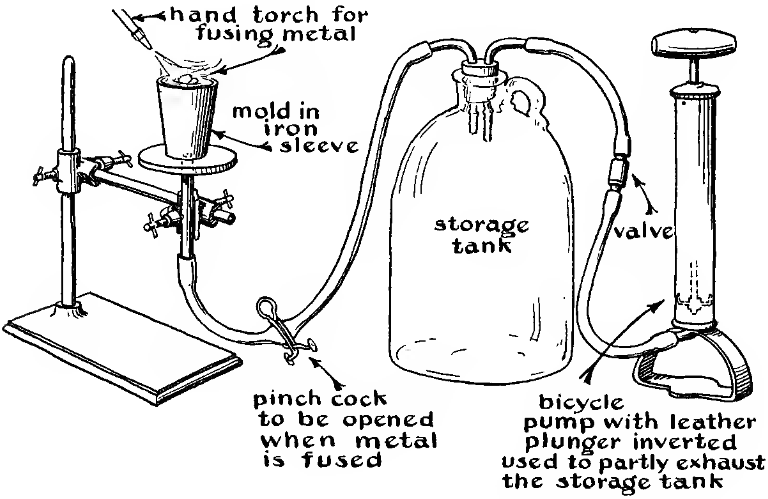


Fig. 7. Lost-wax casting. Vacuum method for filling the mold.

small hand pump is attached to the tank for reducing the air pressure to about one-half to one-fourth atmospheric pressure. The mold is placed on the disk, and the metal is melted in the funnel on the top of the mold with a blast lamp. When the metal is completely molten, the cock is opened, and the air in the mold is drawn out through its porosity, allowing the metal to flow in. Of course, air leaks around the cast, but that does not matter, since the object is to reduce the air pressure in the mold for only a few seconds. This method will make the finest of casts.

Fig. 7 shows a setup of the type described above, which

can easily be assembled with the aid of a bicycle pump and a few accessories.

Another method is to force the metal into the mold with steam. The metal is melted in the top of the mold as before. When it has melted, a large piece of moist clay is quickly pressed down onto the mold. The steam generated will force the metal into the mold. When this method is used, the mold should be placed on a perforated plate to allow the air to escape at the bottom (Fig. 8).

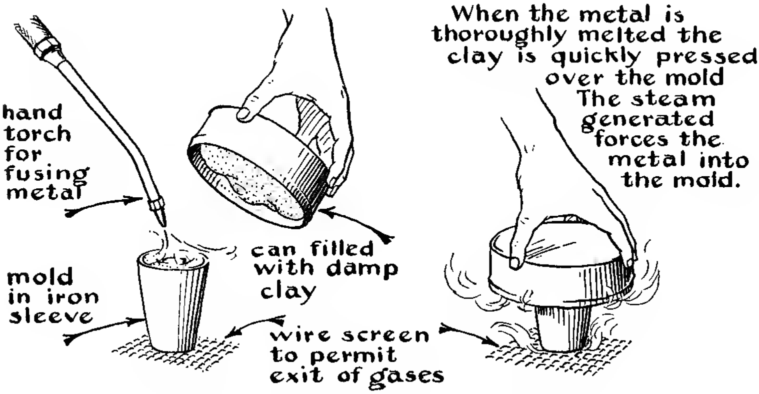


Fig. 8. Lost-wax casting. Steam method for filling the mold.

Still another method introduces the metal into the mold by means of a centrifuge, which need be only a simple device consisting of a bar pivoted to rotate in a horizontal plane. A spring is arranged to rotate the arm, and a movable trigger acts as a stop to prevent the rotation until the metal is molten. The mold is placed in a holder at the end of the arm with its sprue facing the pivot. The crucible, a small trough of firebrick or any other suitable material, is mounted on the arm with the end of the trough adjacent to the sprue. The procedure is to cock the spring, place the mold in the holder, place the metal in the trough, and heat it with a hand torch. When the metal is ready, the trigger is pulled, and the whole arm spins on the pivot, the centrifugal force carrying the metal into the mold. For this method the bottom

of the mold should be made especially strong; otherwise it may give way and the molten metal be thrown about the room. This method is used by commercial jewelers as well as by some dentists. Fig. 9 shows a centrifuge of the type described. For casting the object illustrated in Fig. 1 this method should probably be used, since the top of the mold would hardly be large enough to contain the required amount of metal.

In any of the foregoing methods metals such as gold, silver, copper, brass, and so forth, should be liberally sprinkled with borax as they are fused. This treatment prevents

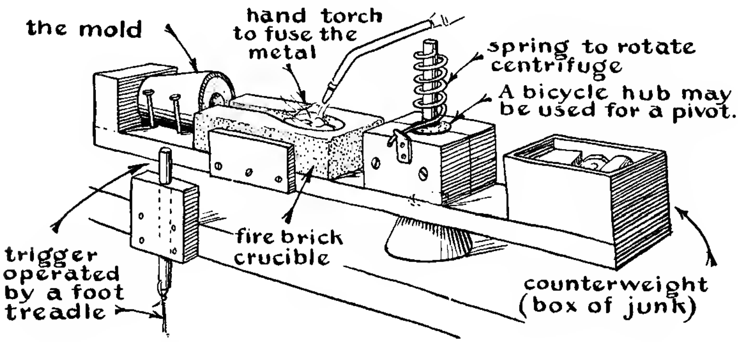


Fig. 9. Lost-wax casting. Centrifuge method for filling the mold.

oxides from forming. Metals such as lead, babbitt, solder, and so forth, may be kept covered with powdered charcoal for the same purpose.

Patterns for sand casting. Sand casting from permanent patterns of metal or wood is the method commonly employed for all manner of mechanical parts, irrespective of size or of metal. Die casting is the only other method of importance, but it is restricted to commercial work in which the otherwise prohibitive cost of the metal dies is absorbed in the tremendous quantity of casts to be produced. In making the patterns for sand casting, the first step is to make a careful drawing of the object (Fig. 10). Over this drawing a second one should be made (Fig. 11), which is the pattern drawing. It can be made on thin paper. For future

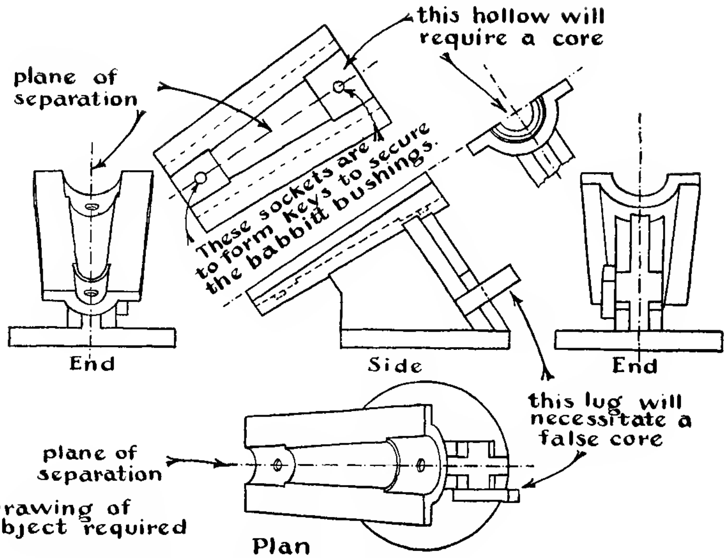


Fig. 10. Sand casting. Mechanical drawing for the polar-axis mounting for a small telescope.

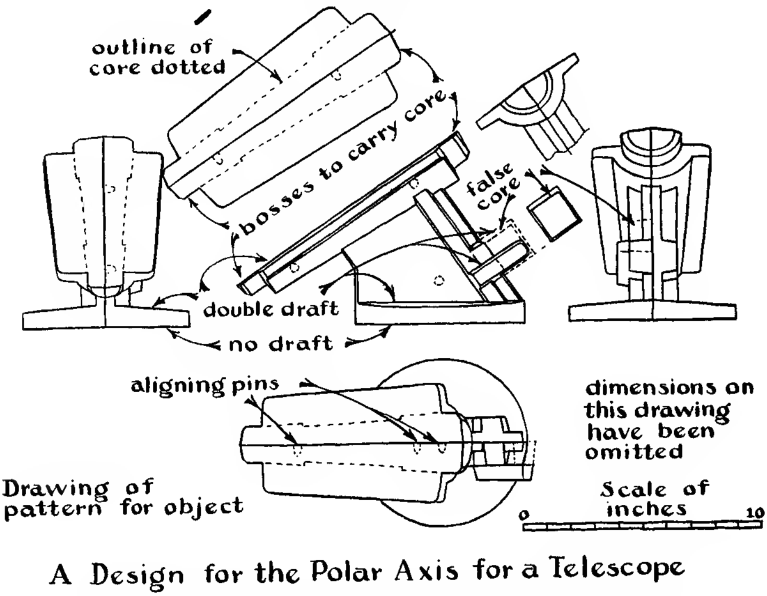


Fig. 11. Sand casting. Mechanical drawing of the pattern.

convenience it is well to dimension the pattern drawing copiously.

As an object for the illustrations that demonstrate sand casting, a polar axis for a telescope has been chosen. The axis is designed to have babbitt bearings. Such a design eliminates the necessity for chucking the whole axis in a lathe and boring it—a job to be accomplished only in a very large lathe. Figs. 10 and 12 show drawings of the parts required, and Fig. 24 shows the completed mounting.

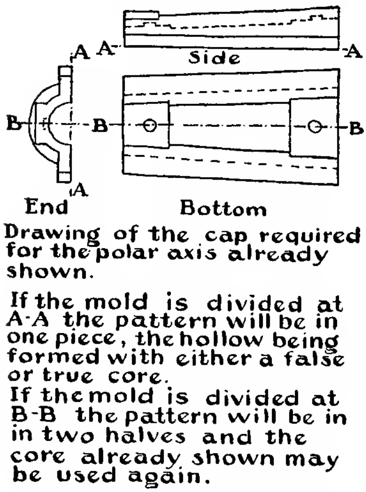


Fig. 12. Sand casting. Drawing of the cap for the polar axis.

In planning the pattern, the first thing that must be determined is the plane of division of the mold. This plane should pass through the object in such a way that both parts of the pattern can be drawn from the sand mold. The plane must intersect the object in such a way that all points on the object, when they are projected normally to the plane, will fall on or within the intersection. It is to this plane that all questions of "draft" are referred. If there is no single plane that will fulfill the requirements, one must be chosen which will come the nearest possible, and the parts that do not conform will have to be accomplished with cores.

The pattern will be divided along the plane of division unless the plane happens to coincide with one surface of the object, in which case the pattern will be in one piece (Fig. 12). Since the usual cases are those in which the pattern must be divided into two halves, we will describe the procedure for a two-piece pattern. The designer need not be limited to the two-piece pattern, but the multi-piece pattern is so seldom employed that it is not within the scope of this chapter to

treat of it. The reader is referred to books on commercial founding.

Since parallel-sided objects can not be withdrawn from sand without the friction of the sides destroying the walls, it is necessary to taper the sides slightly. This taper is called "draft," and it may be as little as $\frac{1}{2}°$ for fine commercial work. In most work, however, 3° is regarded as the proper draft angle. Round objects need no draft when the plane of separation passes through the axis. When the requirements of the object are such that there can be no draft on one of the faces, that is, when that face must be at a right angle with the plane of separation, then the draft on all opposite faces should be doubled (Fig. 11).

If there is a projection on one of the pieces of the pattern that does not touch the dividing plane, then between it and the dividing plane must be provided a separate block which can be removed after that half of the mold is made. This block is called the "false core," and the volume which it occupies in that half of the mold will be replaced by an equal volume of sand in the other half of the mold. The false core must also have draft. It will be seen later in the description of the process for making a mold that false cores must be used on only one piece of the mold, and that this must be the piece which has the holes to receive the pegs that hold the parts of the pattern in alignment. Since this is the part that is molded first, it must be capable of lying flat, with the plane of separation in contact with a table. If false cores are required on the other piece of the mold, they must be regarded as true cores. The blocks must be fixed in place and a core box made for them as will be described later in this chapter.

If there is to be a hole through the object, bosses must be put on the pattern wherever the hole comes through the surface of the object. These bosses are to form sockets in the mold for carrying the ends of the core, thereby preventing its floating in the molten metal. The bosses must have draft angles to conform to the rest of the pattern. Separate

drawings should be made of the cores, the drawings to include the bosses just mentioned (Fig. 18).

A core is any piece of sand or mold material that is molded separately and inserted in a mold, thereby forming a hole or cavity in the finished cast. If the core comes to the surface of the pattern at only one place, the boss to receive it must be long enough to support the core as a cantilever. Should this prove impractical, projections may be made on the core which will bear against the inside of the mold and carry the core. These projections will leave holes in the finished cast which will have to be plugged. Still another way is to use metal supports to carry the core. The supports are in the form of pins with broad heads and crooked shanks, and they are pressed into the sand by the molder. They weld with the metal of the cast. It is well to remember that not only must the core be supported against gravity in the empty mold, but it must also be restrained from floating in the molten metal when the mold is filled.

Since nearly all metals shrink in solidifying, patterns have to be made enough larger to compensate. The amount of shrinkage varies with the metal. A list of shrinkage scales is given in Table I.

TABLE I

SHRINKAGE SCALES

Metal	Shrinkage (inches)	Metal	Shrinkage (inches)
Aluminum	$\frac{3}{16}$	Dow metal alloy	$\frac{5}{32}$ to $\frac{3}{16}$
Aluminum alloys	$\frac{5}{32}$	Gunmetal bronze	$\frac{1}{8}$ to $\frac{3}{16}$
Aluminum bronze	$\frac{1}{4}$	Lead	$\frac{5}{16}$
Brass	$\frac{3}{16}$	Mal. iron	$\frac{1}{8}$
Britannia	$\frac{1}{32}$	Manganese bronze	$\frac{1}{4}$
Bronze	$\frac{3}{16}$	Nickel-steel alloy	$\frac{1}{4}$
Carbon steel	$\frac{3}{16}$ to $\frac{1}{4}$	Phosphor bronze	$\frac{1}{8}$ to $\frac{3}{16}$
Cast iron (gray)	$\frac{1}{10}$ to $\frac{5}{32}$	Steel	$\frac{1}{4}$
Cast iron (white)	$\frac{1}{4}$	Tin	$\frac{1}{12}$
Copper	$\frac{3}{16}$	Vanadium-steel alloy	$\frac{1}{4}$

This shrinkage is the amount that must be added per foot to a pattern. For convenience, shrink rules may be purchased that are the correct amount oversize but are calibrated as ordinary rules.

For patterns that are to be cast many times, it is usual to reproduce the original wooden pattern in aluminum or some other metal, and to use this metal pattern for making the molds. In such case the original wooden pattern must be made large enough to allow for shrinkage of both metals. The allowance should be the sum of the shrinkages of both metals. Metal patterns are better for repeated use, since commercial foundries are quite rough on the wooden ones. Furthermore, several metal patterns may be reproduced from the first wooden one, and from these many molds may be made at a time. Thereby the cost of production is reduced.

The rate of solidification of metal in the mold is a function of the thickness of the metal. Since the greater part of the shrinkage occurs at the instant of solidification, it is apparent that unequal thicknesses of metal in the same pattern will cause a certain amount of distortion and warping. For this reason patterns are usually designed to have as uniform a thickness throughout as possible. Of course, the warping may be unimportant, since small projecting lugs on large casts will be carried by large masses of metal. Nevertheless, care should be exercised in designing the patterns to preserve the equality of thickness. Metals cooling from the molten state do not necessarily shrink evenly as the temperature falls. White cast iron, for instance, shrinks a while, then expands a little, and then continues shrinking. Gray iron expands twice and phosphorous iron three times. Thus, in casts of uneven thickness one part may be shrinking while another is expanding, with the result that the casts will be under stresses. In fact, the casts may be broken by the stresses. The hand wheels that are used to tighten the brakes on freight cars are made with spiral spokes, because the uneven cooling of the thick hub and the thin rim sets up

stresses in the spokes which might break them if they were straight.

Pure metal, such as aluminum, copper, tin, or zinc, may be cast in almost any thickness. The case is different with the alloys, especially with those alloys in which there is a great difference between the melting points of the constituent metals. The alloys cooled slowly have time to grow large crystals. In fact, some of the constituent metals may crystallize out, so that thick alloy castings may be weak and full of crystal pockets. The best thickness for alloy castings

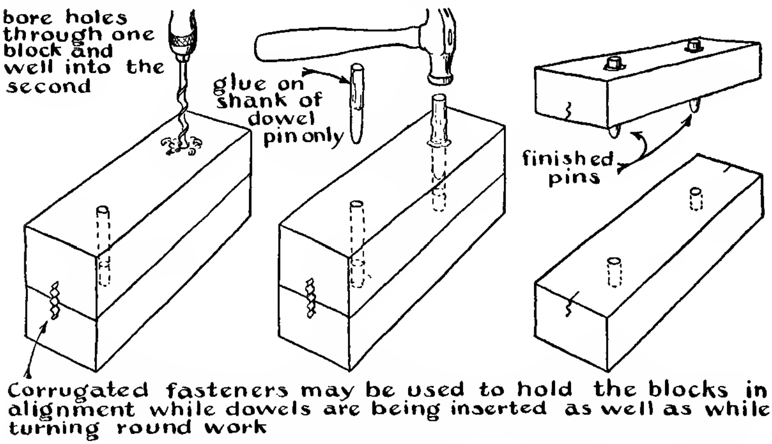


Fig. 13. Sand casting. Method of using wooden dowels to hold the two halves of the pattern in alignment.

seems to be between $\frac{3}{16}$ and $\frac{5}{16}$ inch. Even $\frac{1}{8}$ inch is not too thin. All metals, pure or alloyed, must be cast in a thickness sufficient for the metal to reach all parts of the mold before it sets. However, this matter is not too important, for a good molder can arrange his gates to insure that the molten metal reaches all parts of the mold before it solidifies.

Patterns are usually made of wood—white pine, sugar pine, or mahogany. The wood should be clear and well seasoned. If the pattern is in two pieces (not including false cores), they must be pinned together in such a way that they

can be separated and reassembled by the molder. In making the pattern, it is well first to make the division part with its pins. Wooden dowels may be used, or special pins and sockets, which can be purchased from a hardware dealer (Figs. 13 and 14).

In general, the construction of patterns follows the usual practice in carpentry and cabinetmaking. The parts may

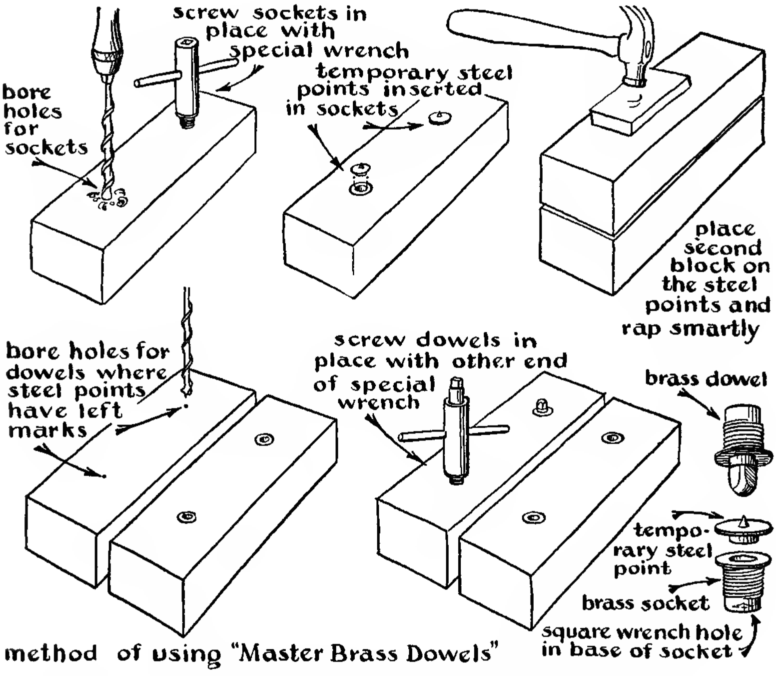


Fig. 14. Sand casting. Method of using patented dowels.

be glued together at will, and all the tricks of joinery may be employed, provided the finished result is the desired shape. The exterior surfaces of the pattern should be carefully smoothed. Any roughnesses or irregularities in the surfaces, particularly in the draft surfaces, will mean that the molder will have to rap the pattern vigorously to free it from the mold, with the result that the mold, and consequently the cast, will be larger than designed.

Each piece of pattern, including the false cores, should be provided with a rapping plate, which is set in flush with the parting face (Fig. 15). These plates can be purchased from a hardware dealer. They provide a hole for rapping and a hole for a lifting screw, or handle, which the molder will use in withdrawing the pattern from the sand.

In making casts it has been found that sharp, internal corners and dihedral angles are a source of trouble. The sharp edges of the mold may crumble, or strains in the metal may cause the cast to break at these corners. To avoid such trouble, it is the practice to round the corners,

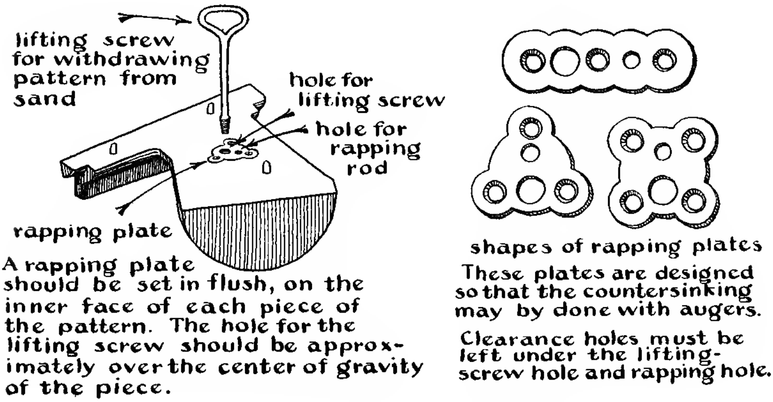


Fig. 15. Sand casting. Rapping plates.

and the corners so rounded are called "fillets." They may be carved in the pattern, but it is easier to make them of wax. The wax can be purchased at hardware stores. It comes on spools or in strips in the form of an extruded ribbon of the proper profile. Before the ribbon is used, the pattern must be shellacked. The ribbon, cut into convenient lengths, is rubbed into place with a hot tool that has a ball-shaped end (Fig. 16). The fillets are sold in sizes according to the radius desired, and the tools can be made or purchased to correspond. After the fillets are finished, the whole pattern is again shellacked. In patterns that are to be used only once the fillets may be made of plastiline or plasticine,

which can be purchased at an artists' supply house. Only the hardest grade should be used. It will stick quite well to the shellacked pattern, and may be modeled with the fingers or with wooden modeling tools. It should be shellacked when it is finished. For larger work, leather fillets can be purchased in many sizes. They are glued directly to the wooden pattern, finished with sandpaper, and shellacked.

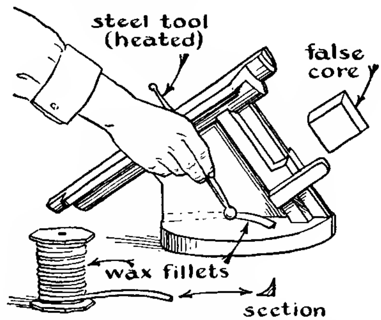


Fig. 16. Sand casting. Method of applying wax fillets.

If there are no cores, clear shellac is used over the whole pattern; but if there are cores, the projections which correspond to the ends of the cores are left in the clear shellac finish or are painted red, while the rest of the pattern is finished with shellac and lampblack. The shellac and lampblack are usually mixed to give a dead black finish. The mixture is liberally thinned with alcohol. The reason for this color distinction is that it tells the molder where the cores belong (Fig. 17).

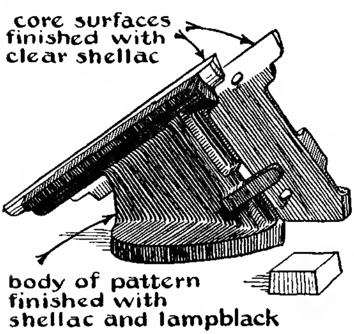


Fig. 17. Sand casting. The finished pattern.

If the pattern has cores, the next problem is to make the core boxes. These are essentially wooden molds, in which the cores are cast. The requirements for draft and shrinkage are the same as for the patterns. If the core requires a two-piece mold, as for cylindrical shapes and the like, the plane of division need have no relation to the plane of division of the original pattern. There is no need to pin the two sides of the core box together, for the two halves of the core are made separately and are stuck together after they are

baked. When the two halves are alike, it is necessary to make a box for only one side. If simple cylindrical cores are required, it is unnecessary to make the boxes at all, for most foundries have stock boxes, or even stock cores. In general, core boxes are carved from solid wood, and they are frequently more complex than the pattern itself (Fig. 19).

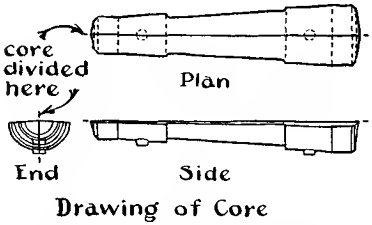


Fig. 18. Sand casting. Mechanical drawing of the core.

The core in the illustration is shown to be made in two pieces, because the surface in the mold which it has to fit has draft. If the pattern had no draft on this top face, the core could easily be in one piece.

Core boxes are made of sugar pine or any other clear and workable wood, and they are finished with shellac like the patterns. One point is important: Since the pattern shows only the ends of the core, and since the core may be unsymmetrical longitudinally, it is well to make the ends different, so that the molder will get the core in the proper orientation.

The process of making cylindrical core boxes, as it has been practiced for years, is very interesting. A core-box plane is used, the face of which is two surfaces at 90° to each other. The plane iron comes through the edge of these surfaces and is sharpened to conform to them. Two parallel lines are drawn on the surface of the stock that is to be used. The plane is made to cut away all the wood possible without removing the two lines. The 90° angle automatically generates a semicircular groove (Fig. 20). The plane can be used to generate conical shapes as well.

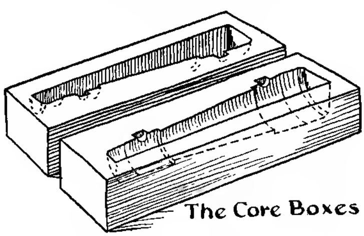


Fig. 19. Sand casting. The core boxes.

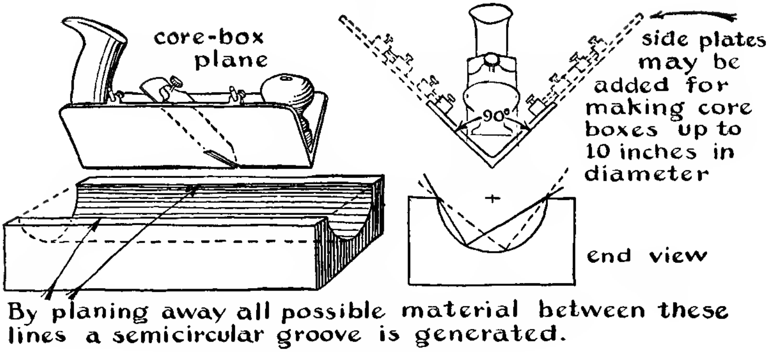


Fig. 20. Core-box plane.

Sand casting. The procedure for making the mold is as follows: The molder first separates the pattern and sets the part that has no pegs with its separation plane face down on the table, putting the false cores in place. Around this piece he puts a wooden or metal frame called a "drag." The "drag" and the "cope" together constitute the "flask," which is a framework to contain the sand forming the mold. The cope and the drag are open rectangular boxes without lid or bottom. They are fitted with crossbars to help hold the sand. There are three sockets in the rim of the drag and three corresponding pins in the rim of the cope which permit them to be separated and reassembled in the same relation as shown in Fig. 21(a).

The molder next sprinkles molding sand through a riddle, or sieve, until the drag is half full. Molding sand is a mixture of fine clear sand and a small amount of clay, and sometimes a little powdered charcoal or graphite. It has been moistened until a handful compressed will retain the print of the hand and will form a fairly firm piece, but moistened not so much but that it can be shaken through a riddle of about $\frac{1}{4}$-inch mesh, the riddle being shaken vigorously. Molding sand is used over and over again with only the addition necessary to replace the inevitable losses.

When the drag has been half filled, the sand is carefully tamped around the pattern. A wooden implement is used

which is about the shape and size of a dumbbell except that one end is flat and the other is a blunt, truncated wedge as shown in Fig. 21(b). More sand is added and tamped until the drag is level, full, and firmly tamped. The sand is then perforated with a thin metal wire to assist the escape of

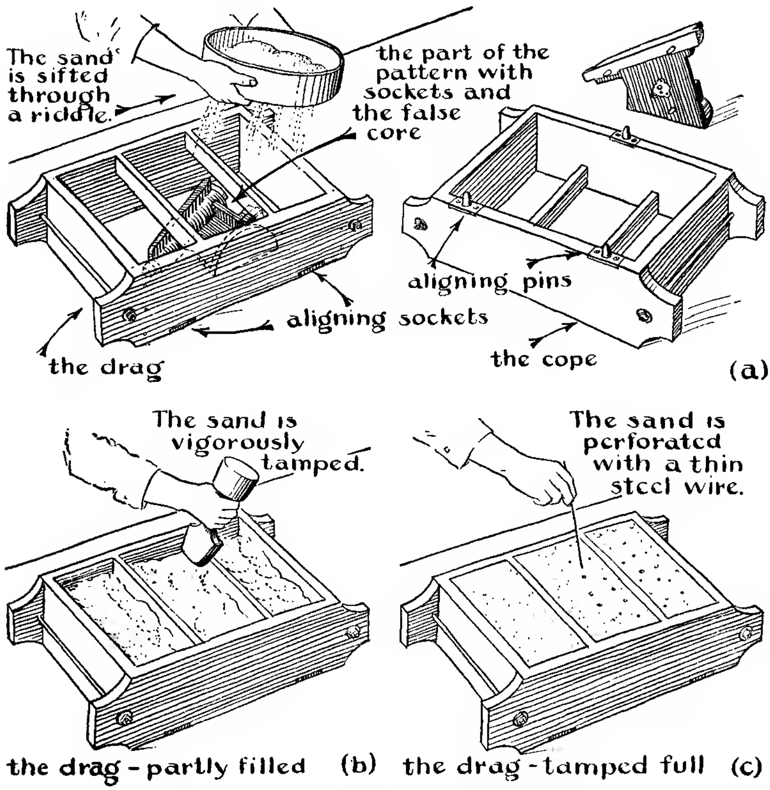


Fig. 21. Sand casting. Filling the drag.

steam and gases that are given off when the metal is poured in. This is illustrated in Fig. 21(c). The drag is now picked up bodily and inverted on the table, exposing the separation face of the pattern. The false cores are removed as shown in Figs. 21(d) and 21(e).

The other half of the pattern is next placed on the part already molded, the pegs insuring alignment of the parts.

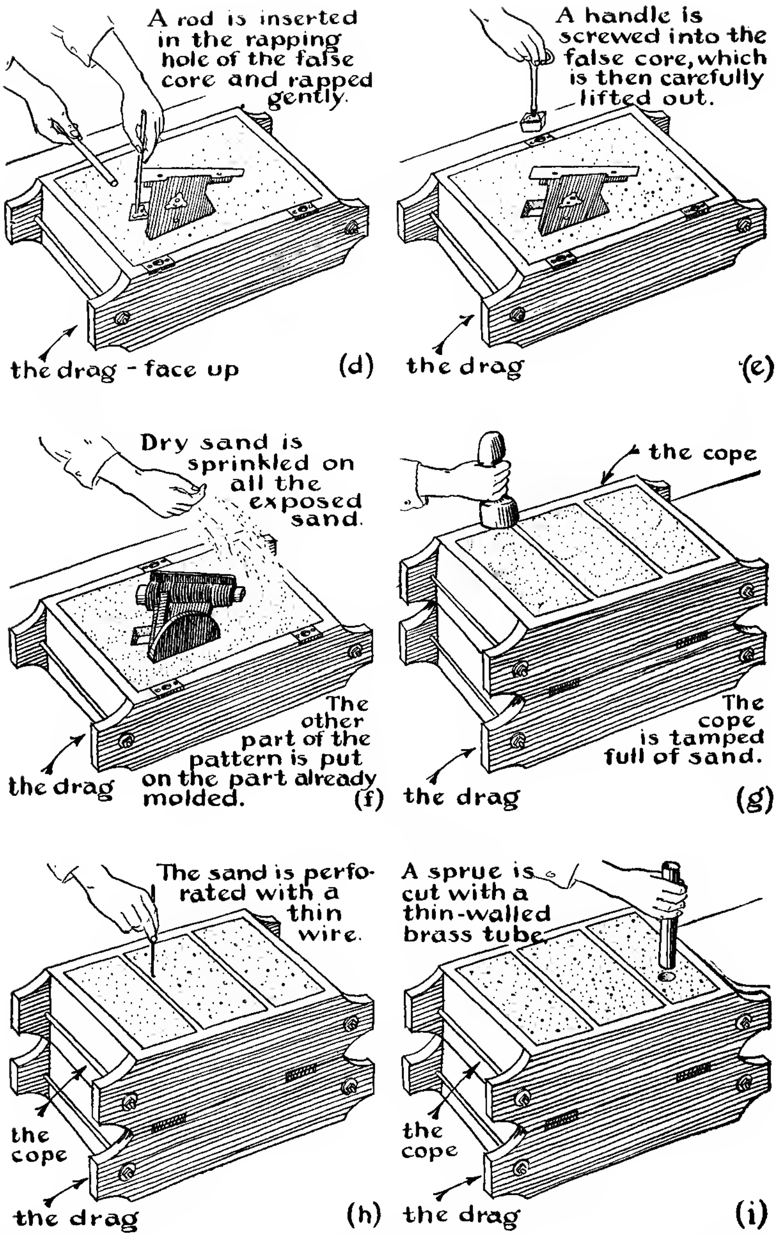


Fig. 21 (continued). Sand casting. Removing the false core and filling the cope.

Dry sand is sprinkled over all the exposed sand of the mold as illustrated in Fig. 21(f) to prevent the two halves of the mold from sticking together. The cope is placed on the drag. It is filled with sand and is tamped, as was the drag, as shown in Fig. 21(g). The sand is pierced many times with a thin wire, as in the case of the drag, in the manner illustrated in Fig. 21(h).

At a point in the sand well clear of the pattern, a sprue is cut deep enough to reach a little below the separation plane. It is cut with a piece of thin-walled brass tubing which is pressed gently into the sand and removed, bringing with it a plug of sand as shown in Fig. 21(i). The hole left is about an inch in diameter, large enough for casts of 10 to 100 pounds. It is well to cut the hole an inch at a time. It is not cut to communicate directly with the pattern, for the force of the descending metal might injure the mold. A trough is cut around the top of the hole as illustrated in Figs. 21(j) and 21(k), and into this the metal will be poured.

The cope is now carefully lifted off the drag and laid beside it, face up. A rod is inserted in the rapping plate and rapped smartly in all directions to break the adhesion of the sand as shown in Fig. 21(l). A handle is screwed into the rapping plate, and the pattern is carefully withdrawn from the sand as illustrated in Fig. 21(m).

A channel, or "gate," is next cut along the parting plane from the mold to the sprue. The reason for not cutting the sprue to communicate directly with the mold is that the sudden rush of heavy metal directly into the mold might injure it. The horizontal gate breaks the fall of the metal as shown in Figs. 21(m) and 21(n).

The mold should be closely inspected for broken corners and edges that must be carefully mended and modeled with steel molder's tools. Bits of sand that have fallen in are brushed away with a soft brush or are blown out with a bellows. A cloth bag half full of powdered graphite is shaken over the mold, and frequently powdered graphite is painted on the surface of the mold with a soft camel's-hair

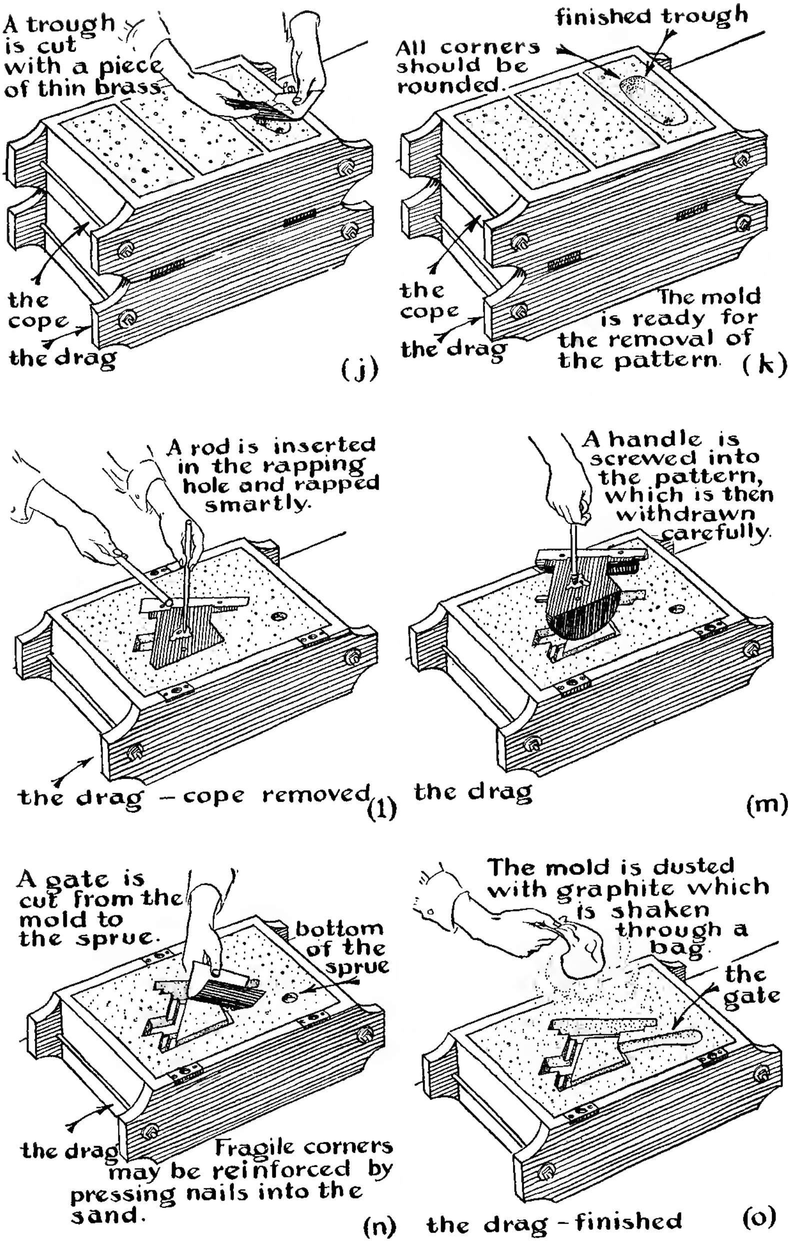


Fig. 21 (continued). Sand casting. Completing the drag.

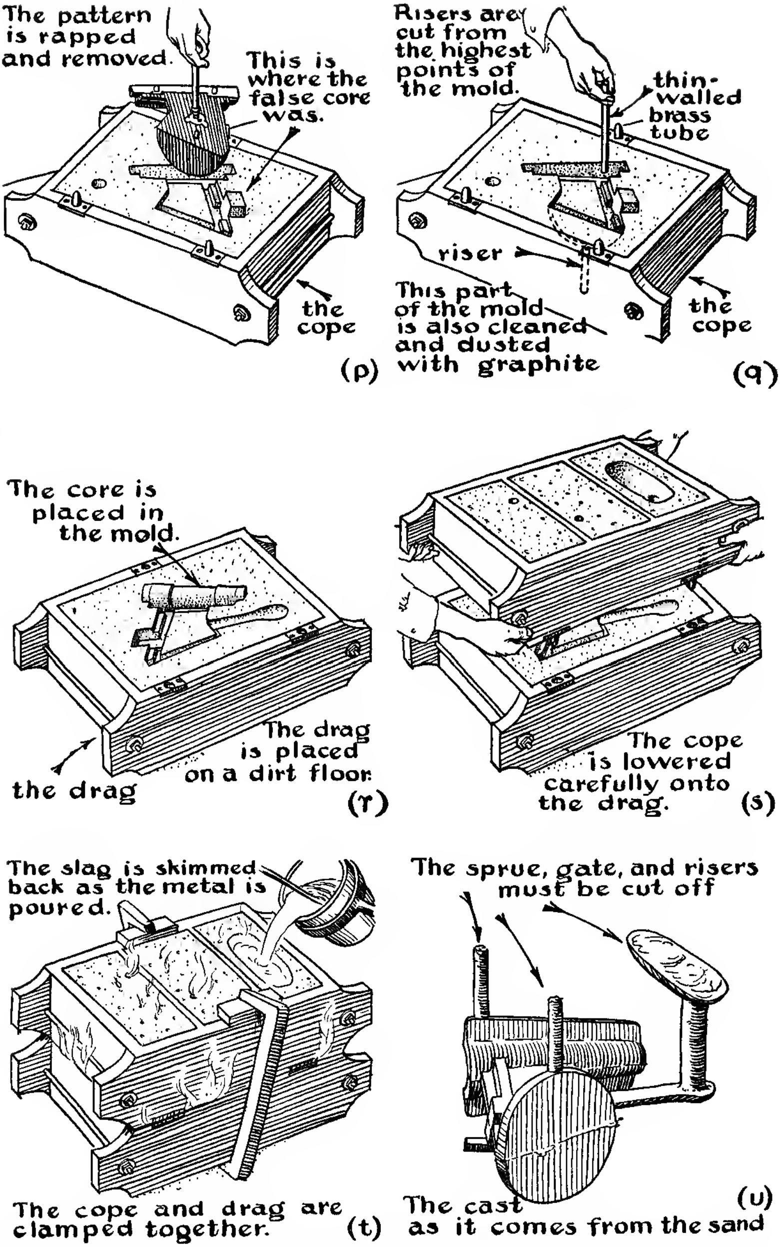


Fig. 21 (concluded). Sand casting. Finishing the cope and filling the mold.

brush as shown in Fig. 21(o). In iron and steel castings this coating of graphite is responsible for the very hard surface layer. Its function is to harden the surface of the mold, and also partly to fill the grainy surface of the sand.

The pattern is removed from the cope as illustrated in Fig. 21(p) in the same manner as from the drag. If the cast is complicated or very large, a riser or several risers are cut in the cope. They are like the sprue, except that they are cut from the highest parts of the mold. In complicated molds they assist in carrying off the entrapped air; in large molds they serve to collect the slag that rises to the surface, and to provide reservoirs for extra metal that will flow back into the mold as the metal within cools and shrinks. This is shown in Fig. 21(q).

The mold is now ready to receive the cores and to be put together. For thin casts in alloy the halves of the mold may be heated with a blowtorch to drive off the water nearest the surface, which otherwise would cool the metal before it had time to flow.

Cores are made by filling the core boxes with a mixture of coarse sand and a binder. The core boxes are tamped full and leveled off with a straightedge. They are then inverted

TABLE II

BINDERS

Binder	Amount
Linseed oil	2 per cent by volume
Molasses	2 per cent by volume
Pitch	5 per cent by weight
Resin	4 per cent by weight

on sheets of metal, rapped, and removed, leaving the halves of the core, which are baked for a few hours in an oven. The baked halves are stuck together with the mixture of which they are made, or with mucilage or paste, and are baked

again (Fig. 22). Pure silica sand which has passed through a 50-mesh screen and has been retained on a 70-mesh screen should be used. Many substances may be used as binders, a complete list of which the reader will find in books on founding. The ones most easily available are given in Table II, together with the amounts to be used.

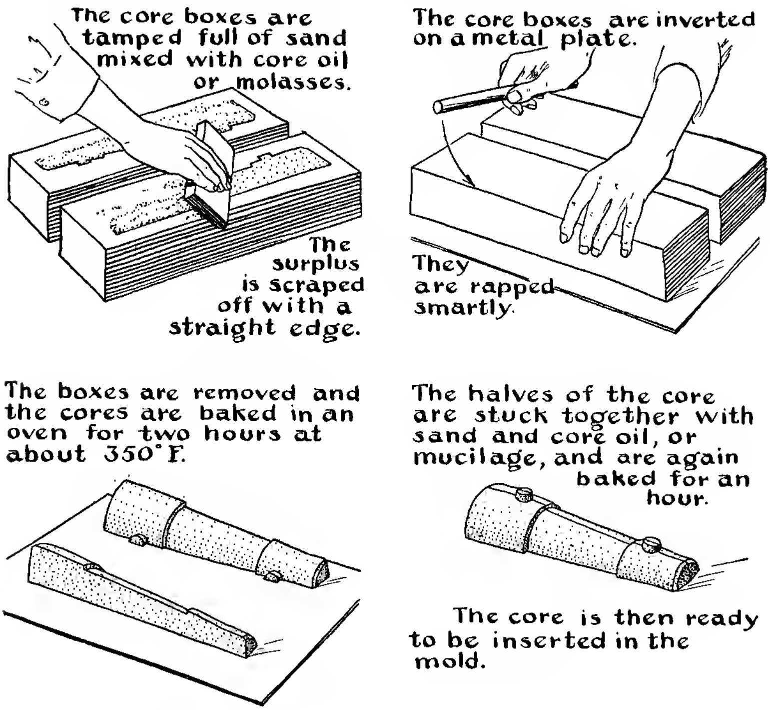


Fig. 22. Sand casting. Making the cores.

If linseed oil is used, the cores must be baked at 425°F. for $1\frac{1}{2}$ hours. For the others 350°F. for $1\frac{1}{2}$ hours will do. Linseed oil makes the strongest cores, and pitch and resin the weakest.

When the cores are thin and fragile, they are frequently reinforced with iron wires. If the cores are very bulky, provision should be made for conducting away the gases that will be formed in them and that will blow the cast apart if

allowed to remain unvented. Such provision is made by laying strips of wax in the sand as the cores are being made. When the cores are baked, the wax is driven off, leaving holes for the gases to escape through.

The completed cores are placed in the molds, and the flask is reassembled. The halves—the cope and drag—should be securely clamped together, for otherwise the metal may actually float the cope off and let out the metal as shown in Fig. 21(t). The mold is now ready to be filled as illustrated in Figs. 21(r) and 21(s).

For production work, when numbers of identical casts are required, match boards are used. These are boards having pins and sockets that correspond to those in the cope and drag, one to fit the cope and one to fit the drag. The two halves of the pattern are permanently fixed to the boards, properly placed to insure correct matching of the two. The halves of the mold are then made separately. They may even be made by separate workmen, and are not assembled until the time for the pouring. In the case of metal patterns several are placed on each board so that a number may be cast at a time.

The molten metal should be poured gently into the mold. It is well to skim back the slag and scum that form on the top of the metal in the crucible or ladle. For the soft metals, which can be handled in iron containers, a kettle having a spout that communicates with the bottom may be used. The floating slag and oxides will be left in the kettle. In molds involving large masses of metal it is common for the workmen to stir the metal in the mold. They churn it up and down in the riser with an iron rod. This action prevents the metal in the riser from solidifying until the outer shell of the cast has set. As the center of the cast sets, the metal in the riser descends and prevents shrinkage pockets from being left in the top of the cast. The escaping gases usually burn briskly, but if they burn too much at the division of the mold, the flames should be doused with water to save the flask from being badly charred.

Large casts are usually left overnight to cool. Smaller ones may be immediately dug out of the mold. In fact, it is the practice in a certain instrument company to remove the small casts immediately from the sand and throw them red hot into the water. The steam generated blows away the sand and even blows out the cores, leaving the casts virtually clean.

When the sprues and gates and risers have been cut off, the cast is ready to be machined or otherwise finished as shown in Fig. 21(u).

In having the casts made it is often desirable to estimate the weight of the finished casts before they are ordered. Such an estimation is easily made: Weigh the pattern, allow for the cores, and multiply the result by a coefficient which is the ratio of the weight of the pattern material to the weight of the metal of the cast. A short list of these coefficients is given in Table III.

TABLE III

RATIO OF WEIGHTS OF FINISHED CASTS TO WOOD PATTERNS

Metal	White pine 26 lbs. per cu. ft.	Mahogany or yellow pine 34 lbs. per cu. ft.
Cast iron (gray) 449 lbs. per cu. ft.	17.3	13.2
Mal. iron 474 lbs. per cu. ft.	18.2	13.9
Steel 480 lbs. per cu. ft	18.4	14.1
Copper alloy 535 lbs. per cu. ft.	20.6	15.7
Aluminum alloy 180 lbs. per cu. ft.	6.9	5.3

If one is making one's own casts, enough metal must be figured to include the sprues and risers. Foundries do not

charge for this metal, since they cut it off and use it over again.

Babbitt metal is essentially a mixture of lead and tin with the addition of enough antimony to cause the metal to expand slightly when it freezes. Many variations of this alloy

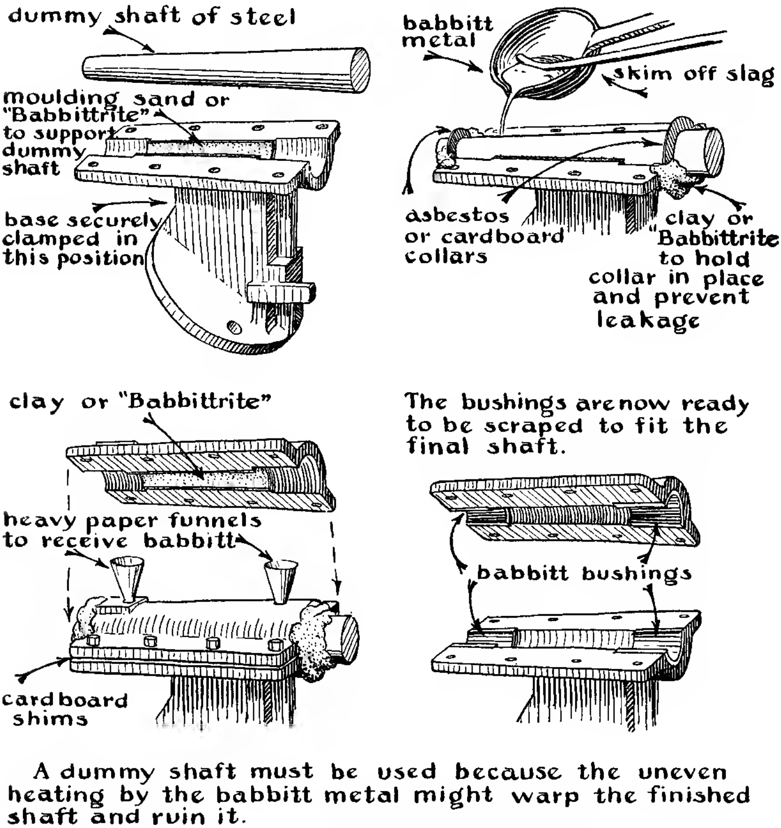


Fig. 23. Method of making a babbitt bearing.

are commercially available having different properties, some being suitable for high-speed bearings and others for bearings which must work under heavy loads. Bearings of babbitt are usually cast in some sort of carrier, so that the babbitt forms a bushing. These bearings are sometimes cast as

solid plugs, which are then bored and reamed to size. More frequently they are cast in two halves with a dummy shaft in place. For many purposes such bearings are good enough just as they are, but for precision bearings they should be scraped to fit the spindle. A dummy shaft should always be used, because the hot babbitt metal is apt to warp the shaft. Fig. 23 shows the method of casting a split bearing.

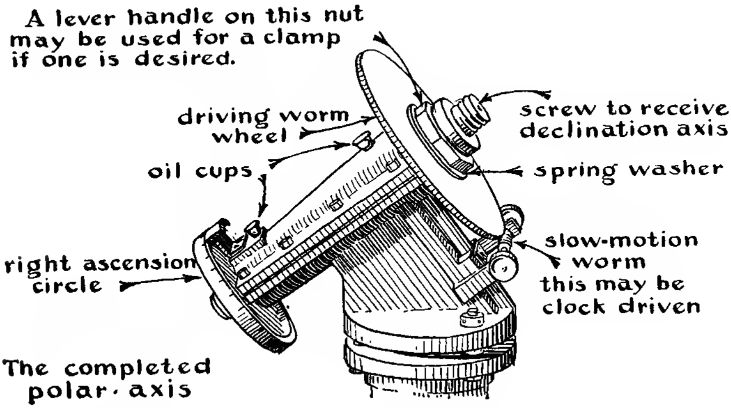


Fig. 24. The completed polar axis for a small telescope.

Cuttlebone casting. There remains one other method of casting which might be found useful in the laboratory. This is cuttlebone casting. The desirable properties of the method are the ease and rapidity with which a cast can be produced: A mold can easily be made and filled in half an hour. The objects to be cast should not exceed the dimensions of $\frac{1}{4}$ inch in thickness, $1\frac{1}{2}$ inches in width, and 3 inches in length. The patterns should be of metal, since they must be subjected to pressure. Draft angles can be very slight, or they may be ignored altogether. There can be no cores. Fig. 25 shows the method quite clearly. Cuttlebones can be procured from a pet shop or drug store for a few cents. The soft, calcareous face is easily crushed and takes a very firm imprint of any object that is pressed into it. Difficulty of pressing thick patterns into the cuttlebone can be overcome

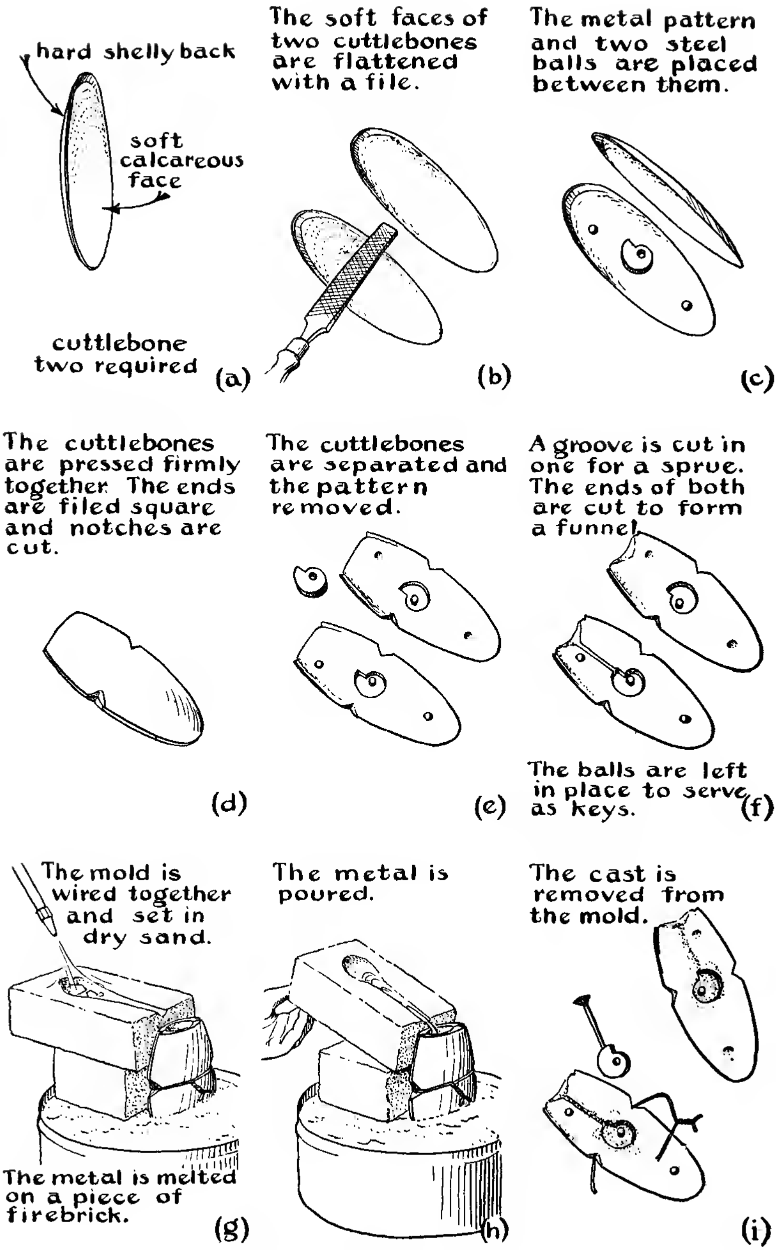


Fig. 25. Cuttlebone casting.

by repeatedly pressing the pattern into the bone, the crushed material being brushed out of the imprint after each operation. The cuttlebone will stand quite high temperatures and is sufficiently porous to allow the air in the mold to escape.

Subject Index

D

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